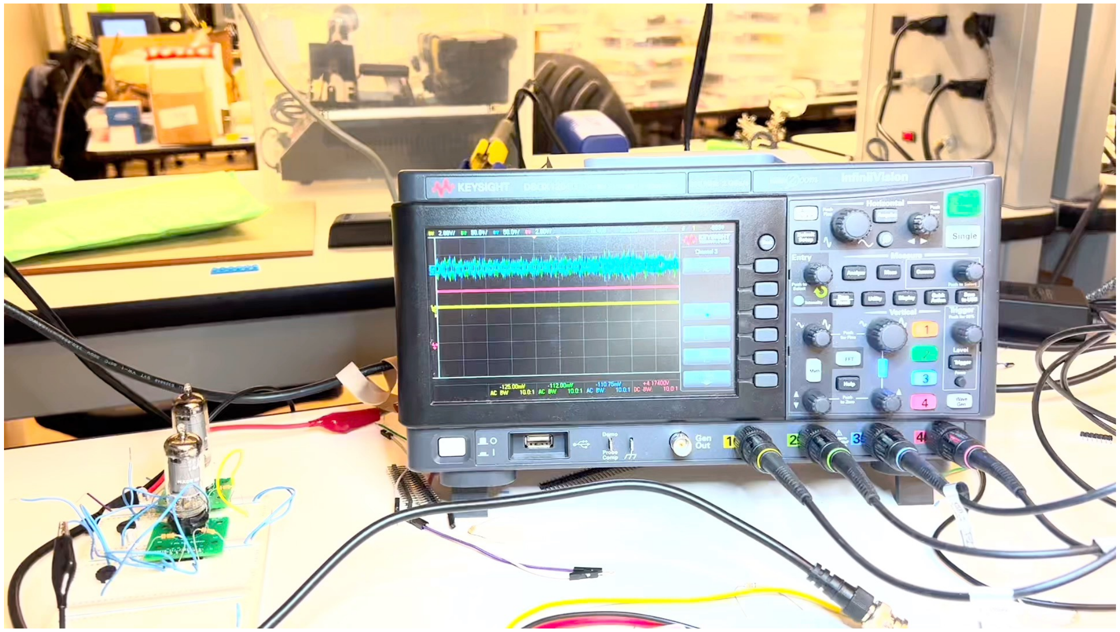
Lecture 7

Tube Electronics

Administrative Stuff

- I think we'll make today the last lecture
  - Classes start next week…I've got advising meetings and prep for 1903/4 and 6.9000. Sorry
- Lab 04 is out. Stuff will remain in lab through Friday evening
- Lab 04 you can make an actually kinda decent Germanium Transistor Audio Amplifier



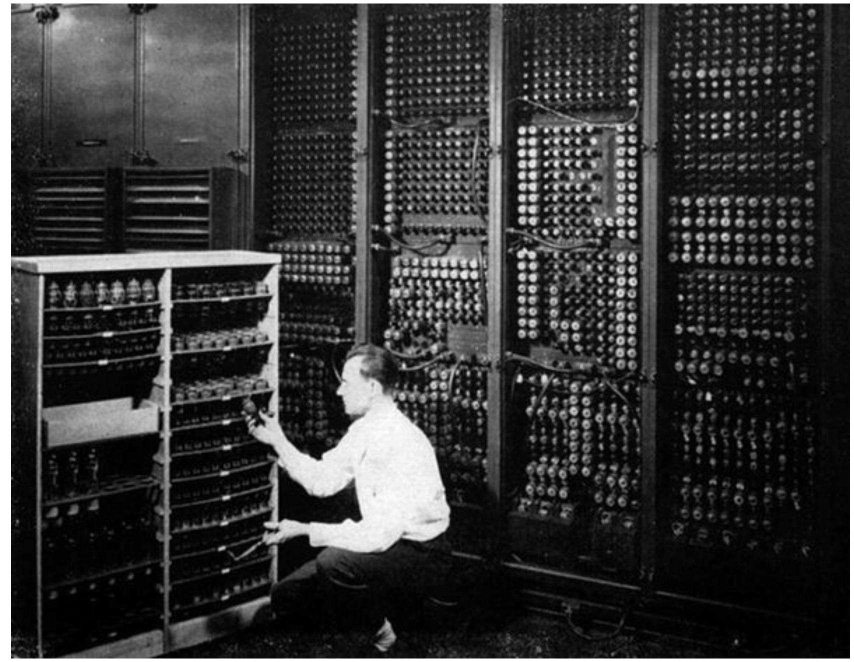
Anywho…

Living with Tubes

- Tubes are really cool tech, but they had their issues:
  - Very delicate
  - Limited life-time (eventual burnout and then you had to replace)
  - Could only be shrunken so far
  - Very power hungry
  - Needed high voltage…even as they made smaller tubes, these would still need 40, 50, 60V and current consumption would best be measured in Amps (not mA)

Tubes Burned Out A Lot

- Tubes are just like filament lightbulbs.
- Eventually the filament goes bad and then you don't get
- What's worse is it could sometimes be a catastrophic cessation of operation…rather gradual fading…so therefore the tube's characteristics would gradually float down



Guy Tracking down which tube burned out out of the 18,000 that made up the ENIAC computer

A lot of early debugging techniques were built around tracking down which tubes were going bad.

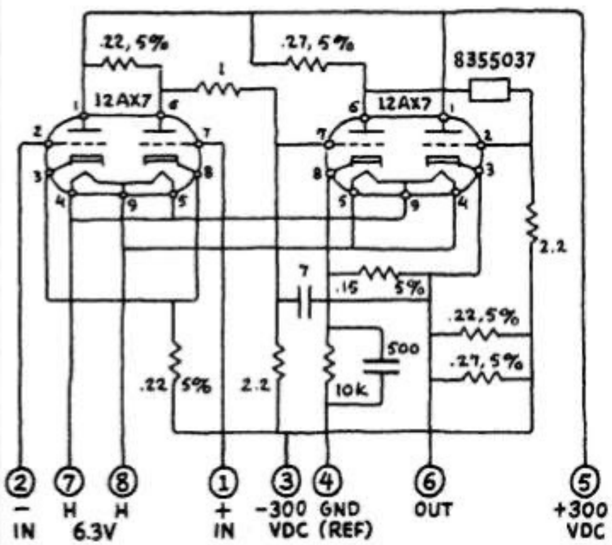
https://www.computerhistory.org/revolution/birth-of-the-computer/4/78/325

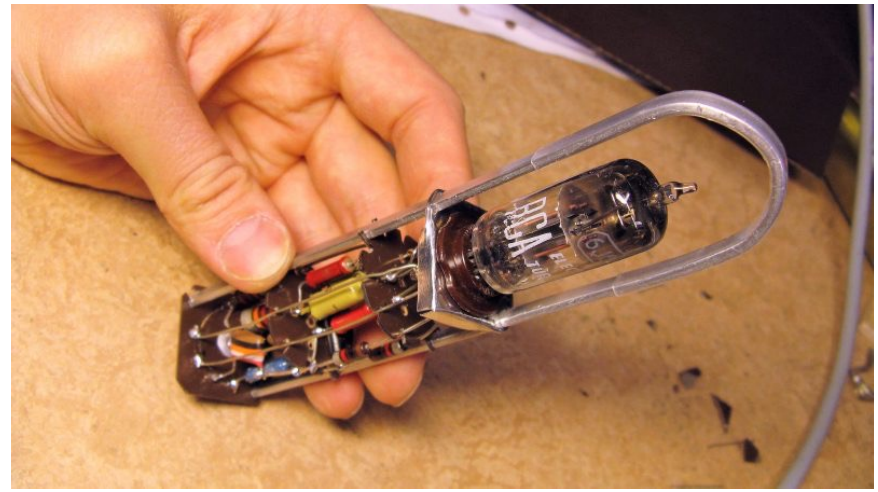
Tubes Consumed A Lot of Power

- ENIAC used something like *170 kW* to run
  - 5,000 additions or 50 multiplications per second
- 2023 M2 Ultra 24-Core CPU & 76-Core GPU, 192GB unified memory uses *330 W* *maximum (standard is like 49W)*
  - ~50 billion multiplications per second and that's without the GPU and neural cores.

We did a lot with Tubes

- Most modern designs started with tubes.

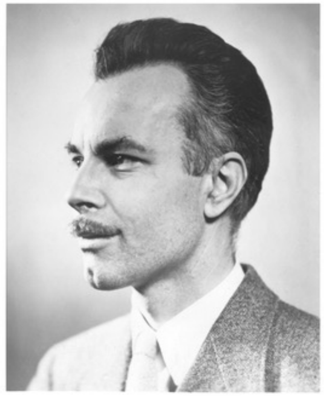




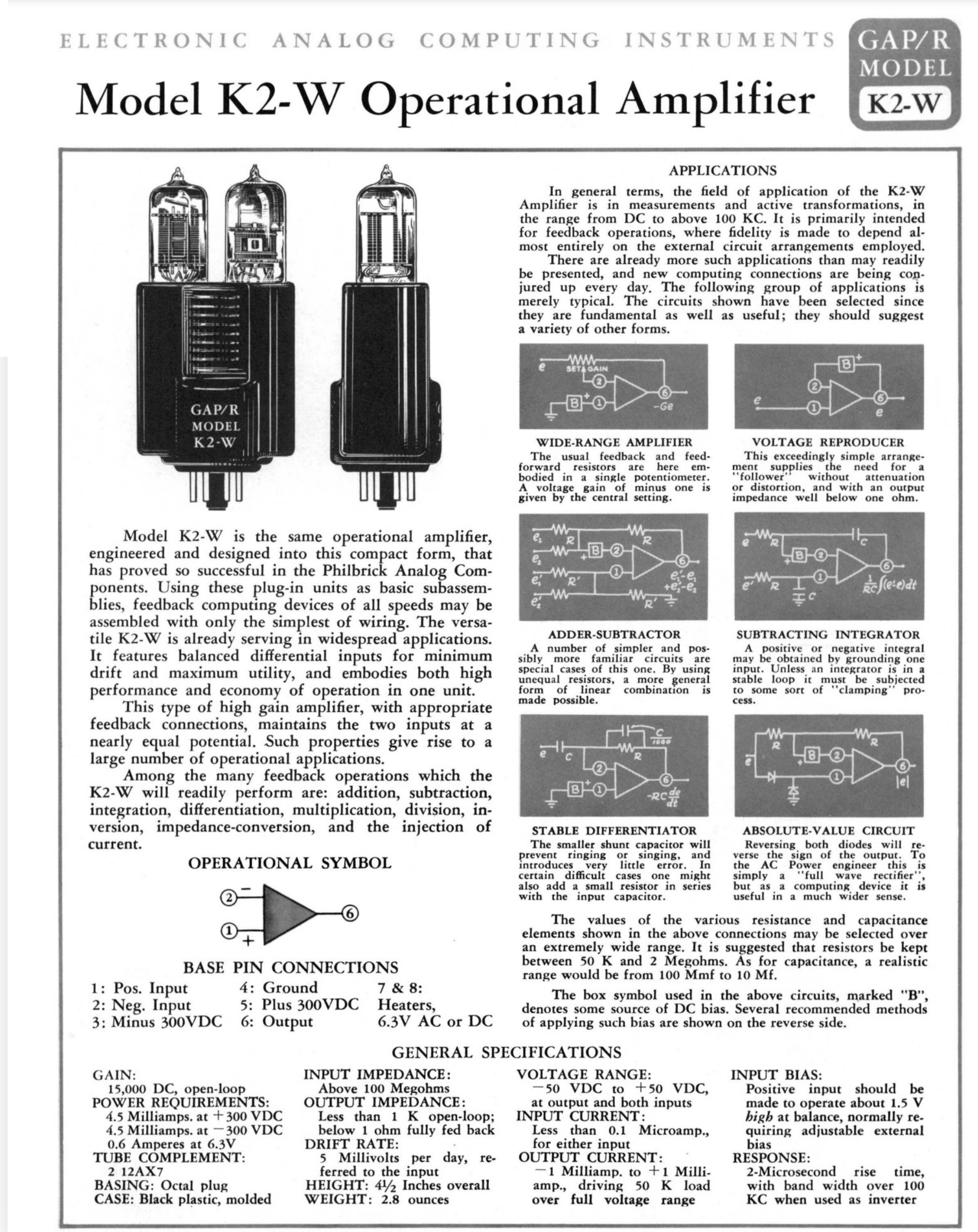
Triode-based Flip-Flop
From IBM 605

https://www.talkbass.com/threads/tube-op-amps-experience-interests.1215611/

Op Amps



- George Philbrick developed op amps and sold tube-based ones right out of Cambridge/Boston
- Building block of much modern analog circuitry



ELECTRONIC ANALOG COMPUTING INSTRUMENTS

GAP/R MODEL K2-W

Model K2-W Operational Amplifier

GAP/R MODEL K2-W

Model K2-W is the same operational amplifier, engineered and designed into this compact form, that has proved so successful in the Philbrick Analog Components. Using these plug-in units as basic subassemblies, feedback computing devices of all speeds may be assembled with only the simplest of wiring. The versatile K2-W is already serving in widespread applications. It features balanced differential inputs for minimum drift and maximum utility, and embodies both high performance and economy of operation in one unit.

This type of high gain amplifier, with appropriate feedback connections, maintains the two inputs at a nearly equal potential. Such properties give rise to a large number of operational applications.

Among the many feedback operations which the K2-W will readily perform are: addition, subtraction, integration, differentiation, multiplication, division, inversion, impedance-conversion, and the injection of current.

OPERATIONAL SYMBOL

BASE PIN CONNECTIONS

1: Pos. Input
2: Neg. Input
3: Minus 300VDC
4: Ground
5: Plus 300VDC
6: Output
7 & 8: Heaters, 6.3V AC or DC

APPLICATIONS

In general terms, the field of application of the K2-W Amplifier is in measurements and active transformations, in the range from DC to above 100 KC. It is primarily intended for feedback operations, where fidelity is made to depend almost entirely on the external circuit arrangements employed.

There are already more such applications than may readily be presented, and new computing connections are being conjured up every day. The following group of applications is merely typical. The circuits shown have been selected since they are fundamental as well as useful; they should suggest a variety of other forms.

WIDE-RANGE AMPLIFIER

The usual feedback and feedforward resistors are here embodied in a single potentiometer. A voltage gain of minus one is given by the central setting.

VOLTAGE REPRODUCER

This exceedingly simple arrangement supplies the need for a "follower" without attenuation or distortion, and with an output impedance well below one ohm.

ADDER-SUBTRACTOR

A number of simpler and possibly more familiar circuits are special cases of this one. By using unequal resistors, a more general form of linear combination is made possible.

SUBTRACTING INTEGRATOR

A positive or negative integral may be obtained by grounding one input. Unless an integrator is in a stable loop it must be subjected to some sort of "clamping" process.

STABLE DIFFERENTIATOR

The smaller shunt capacitor will prevent ringing or singing, and introduces very little error. In certain difficult cases one might also add a small resistor in series with the input capacitor.

ABSOLUTE-VALUE CIRCUIT

Reversing both diodes will reverse the sign of the output. To the AC Power engineer this is simply a "full wave rectifier", but as a computing device it is useful in a much wider sense.

The values of the various resistance and capacitance elements shown in the above connections may be selected over an extremely wide range. It is suggested that resistors be kept between 50 K and 2 Megohms. As for capacitance, a realistic range would be from 100 Mmf to 10 Mf.

The box symbol used in the above circuits, marked "B", denotes some source of DC bias. Several recommended methods of applying such bias are shown on the reverse side.

GENERAL SPECIFICATIONS

GAIN: 15,000 DC, open-loop
POWER REQUIREMENTS: 4.5 Milliamps. at +300 VDC; 4.5 Milliamps. at −300 VDC; 0.6 Amperes at 6.3V
TUBE COMPLEMENT: 2 12AX7
BASING: Octal plug
CASE: Black plastic, molded
INPUT IMPEDANCE: Above 100 Megohms
OUTPUT IMPEDANCE: Less than 1 K open-loop; below 1 ohm fully fed back
DRIFT RATE: 5 Millivolts per day, referred to the input
HEIGHT: 4½ Inches overall
WEIGHT: 2.8 ounces
VOLTAGE RANGE: −50 VDC to +50 VDC, at output and both inputs
INPUT CURRENT: Less than 0.1 Microamp., for either input
OUTPUT CURRENT: −1 Milliamp. to +1 Milliamp., driving 50 K load over full voltage range
INPUT BIAS: Positive input should be made to operate about 1.5 V *high* at balance, normally requiring adjustable external bias
RESPONSE: 2-Microsecond rise time, with band width over 100 KC when used as inverter

http://www.philbrickarchive.org/k2-w_refurbished.pdf

The Problem(s) with Tubes

- A solid-state vacuum tube was dreamt of for decades
- Reliable semiconductor diodes were a thing by the 20's but the **semiconductor triode** was elusive
- Lilienfield made and patented an early working (Field Effect Transistor) FET in the 1920s, but this work was largely ignored
  - Semiconductors weren't good quality to take advantage of it
  - Tubes were dominant so seen as more of a curiousity

Transistors

- WW2 motivated a lot of research into a lot of areas.
- One of these was in creating more refined semiconductors for making better mixer diodes which could be better than tube diodes
- During this work people started to wonder if the same pattern could apply to triodes
- Multiple groups worked on problem
- The “winners” were these three

ttps://en.wikipedia.org/wiki/History_of_the_transistor

Transistors

- Mid-afternoon on Dec 23, 1947, these three guys demo-ed a working transistor to staff at Bell Labs (PNP-germanium transistor with gain of 18).

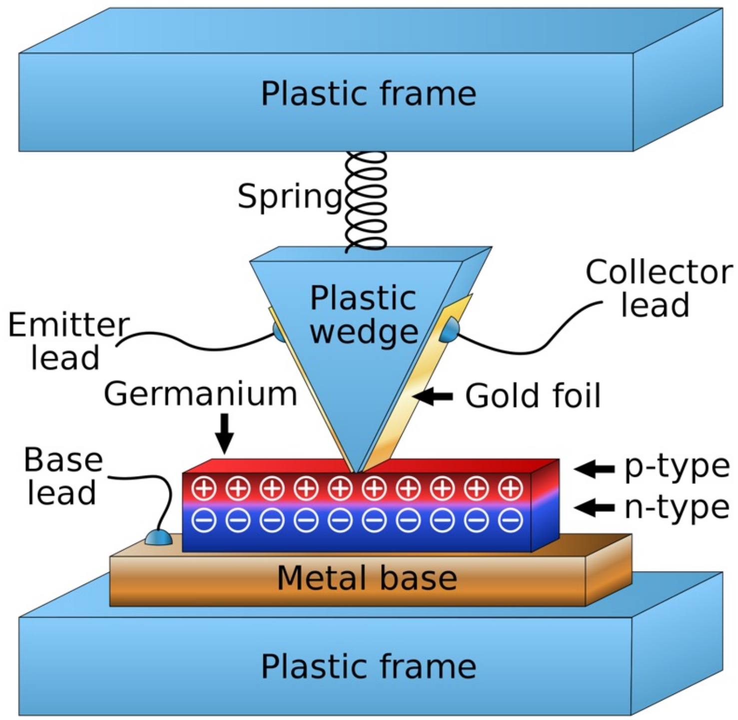
William Shockley
MIT, PhD '36, sadly…

John Bardeen
One of only two people to have won two Nobels. Marie Curie was other!

Walter Brattain

https://www.computerhistory.org/revolution/digital-logic/12/273

The Point-Contact Transistor



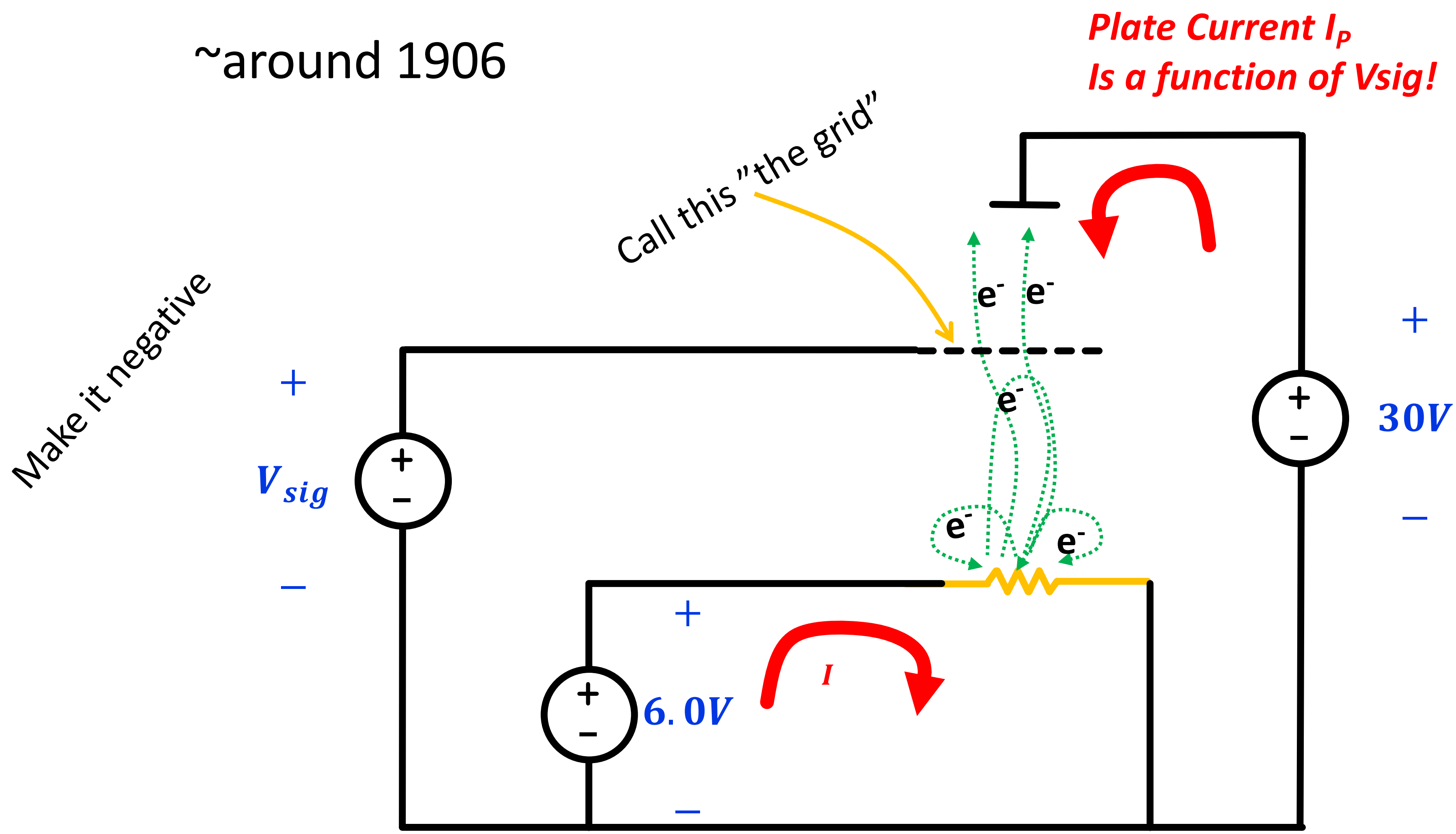
https://www.computerhistory.org/revolution/digital-logic/12/273

Point Contact is weird transistor

- Very hard to manufacture
- Very, very delicate
- Its size and lower voltage were the only things it had going for it, but the first two issues did not make it very competitive with tubes.
- Shockley kept working and eventually came up with the more “modern” junction transistor comprised of three layers of silicon of different “types”
- In 1951 he patented the Junction transistor which is the first “modern” transistor which we still use today.

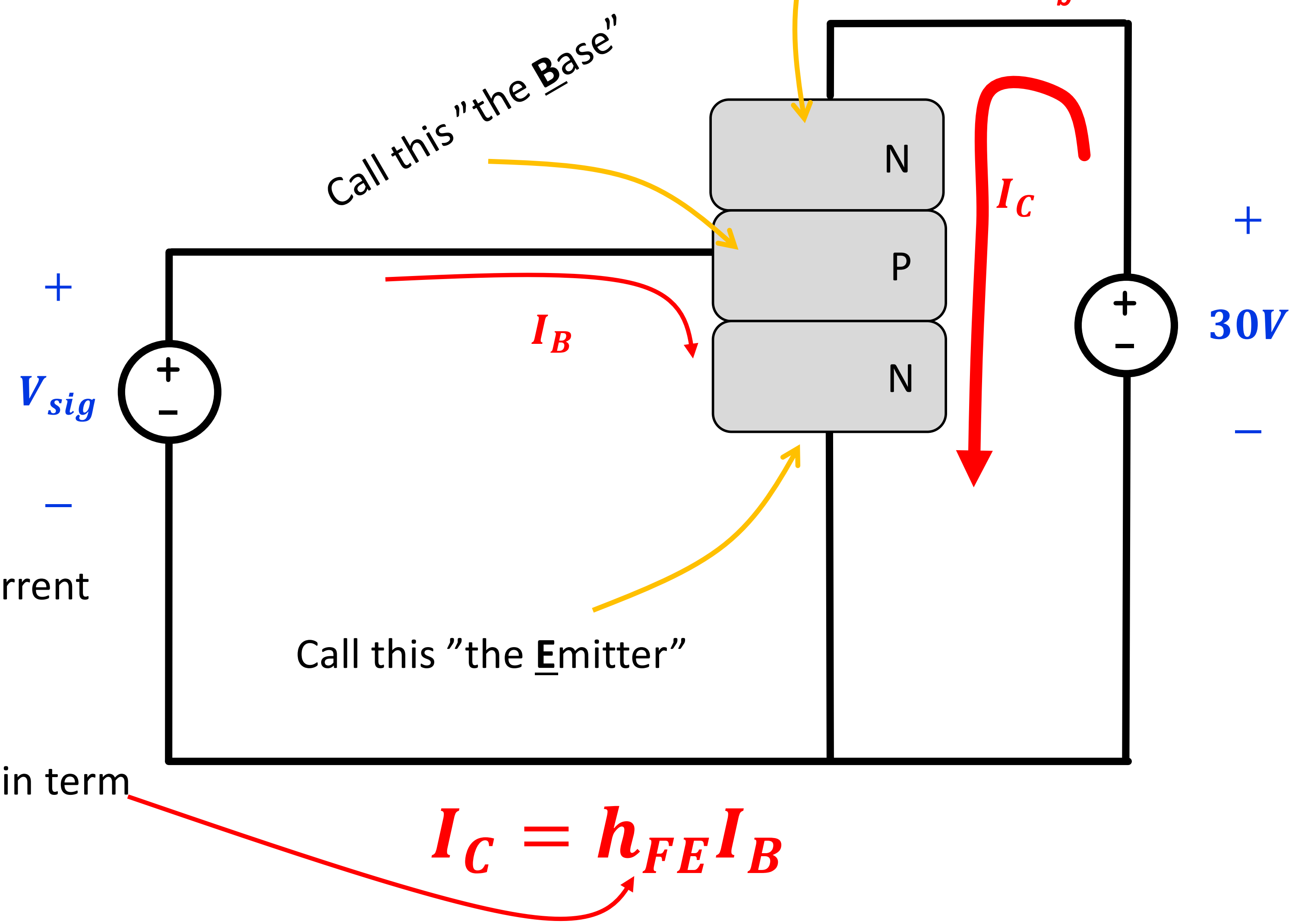
Remember the Triode

~around 1906



The Solid-State Triode

~around 1950/1



A small current

Your gain term

$$I_C = h_{FE} I_B$$

First Big Departure from Tubes: How Signal is Controlled!

- Tubes were (largely) devices that used a voltage to modulate a current (varying grid voltage would vary plate->cathode current)
- Early Transistors were devices that used a current to modulate a current (varying current from base-to-emitter would vary current from collector-to-emitter)
- ***Big departure!***

Implications

- Since junction transistors relied on putting in an input current and amplifying it that meant that the input impedance of the device was generally lower than that of a tube:
  - Remember, when a triode was operating with a negative grid-cathode voltage, current into the grid was negligible.
- Coupling and connections between stages needed to be done differently

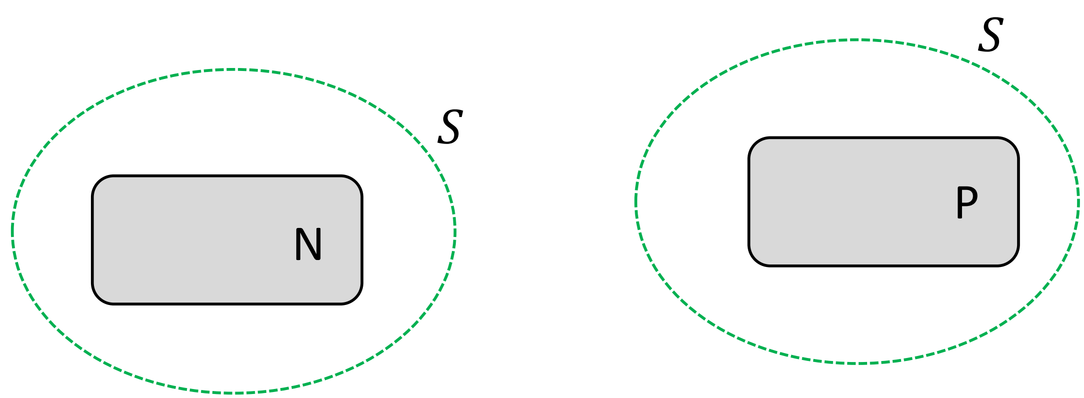
Semiconductors

- Once semiconductor crystals could be made with high purity they decided to ”dope” them with certain atoms to make their crystal structures have either excesses of electrons or lacks of electrons (holes)
- Rarely was “pure” semiconductor used…it was usually doped into two types:
  - “N”-type (had excess of mobile electrons)
  - “P”-type (had excess of mobile “holes”)

N and P type Semiconductors

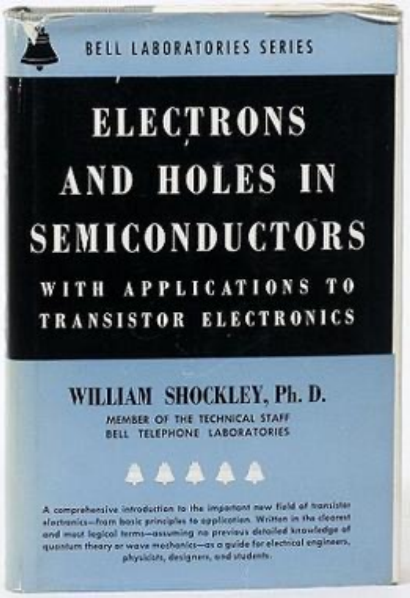
- N-type is ***NOT*** negatively charged…it is electrically neutral…it just has electrons which are “mobile”
- P-type is ***NOT*** positively charged…it is electrically neutral…it just has holes which are “mobile”

$$\oiint_S E \, dS = 0$$



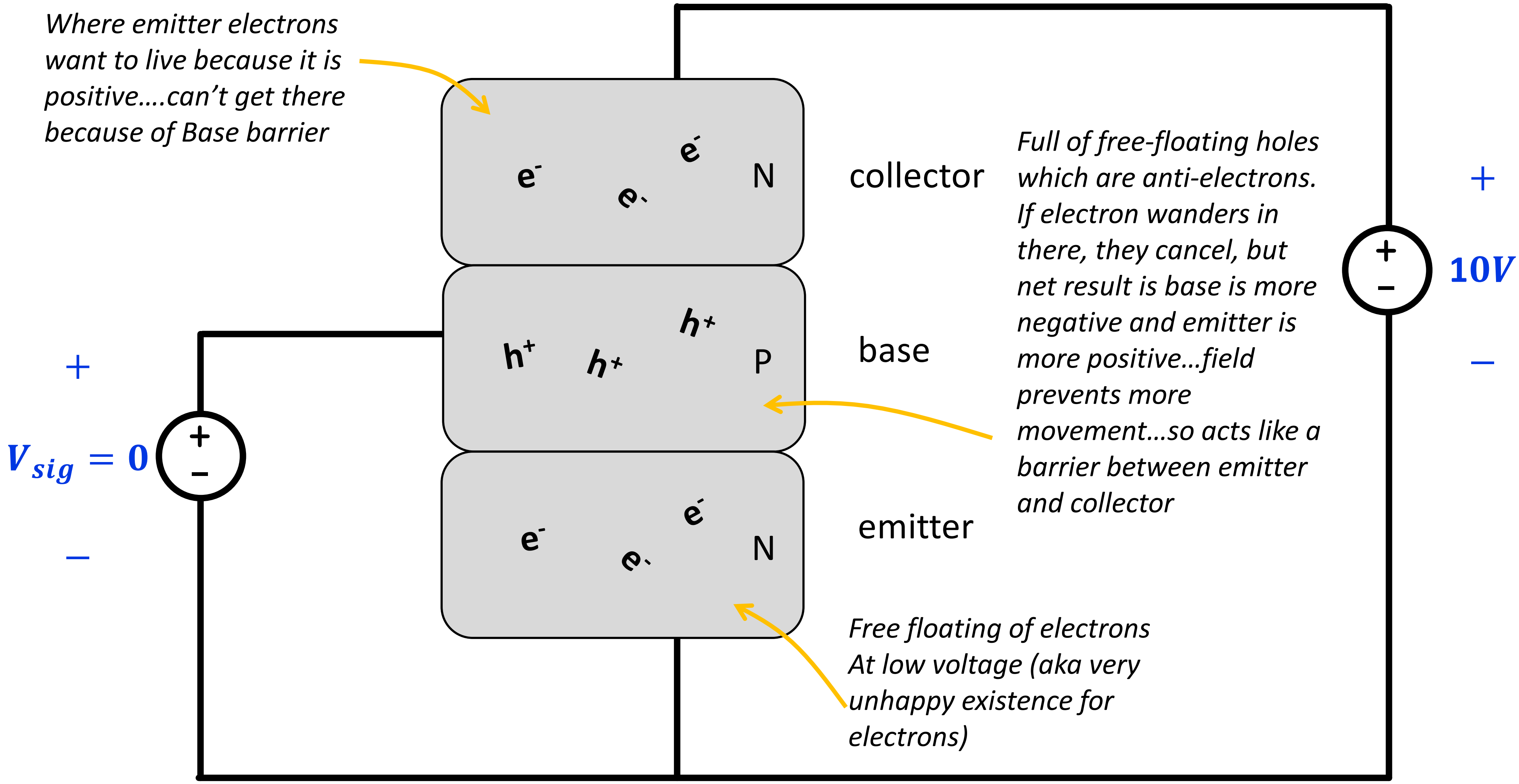
What is a Hole?

- It is a “quasi-particle”. A missing electron in a crystal lattice can roughly be thought of as a particle of negative e^- in charge.
- One analogy is how “gaps” in a traffic jam will move opposite the flow of traffic and from a distance it looks like “anti-cars” are moving
- Analogy taken from Shockley’s famous book



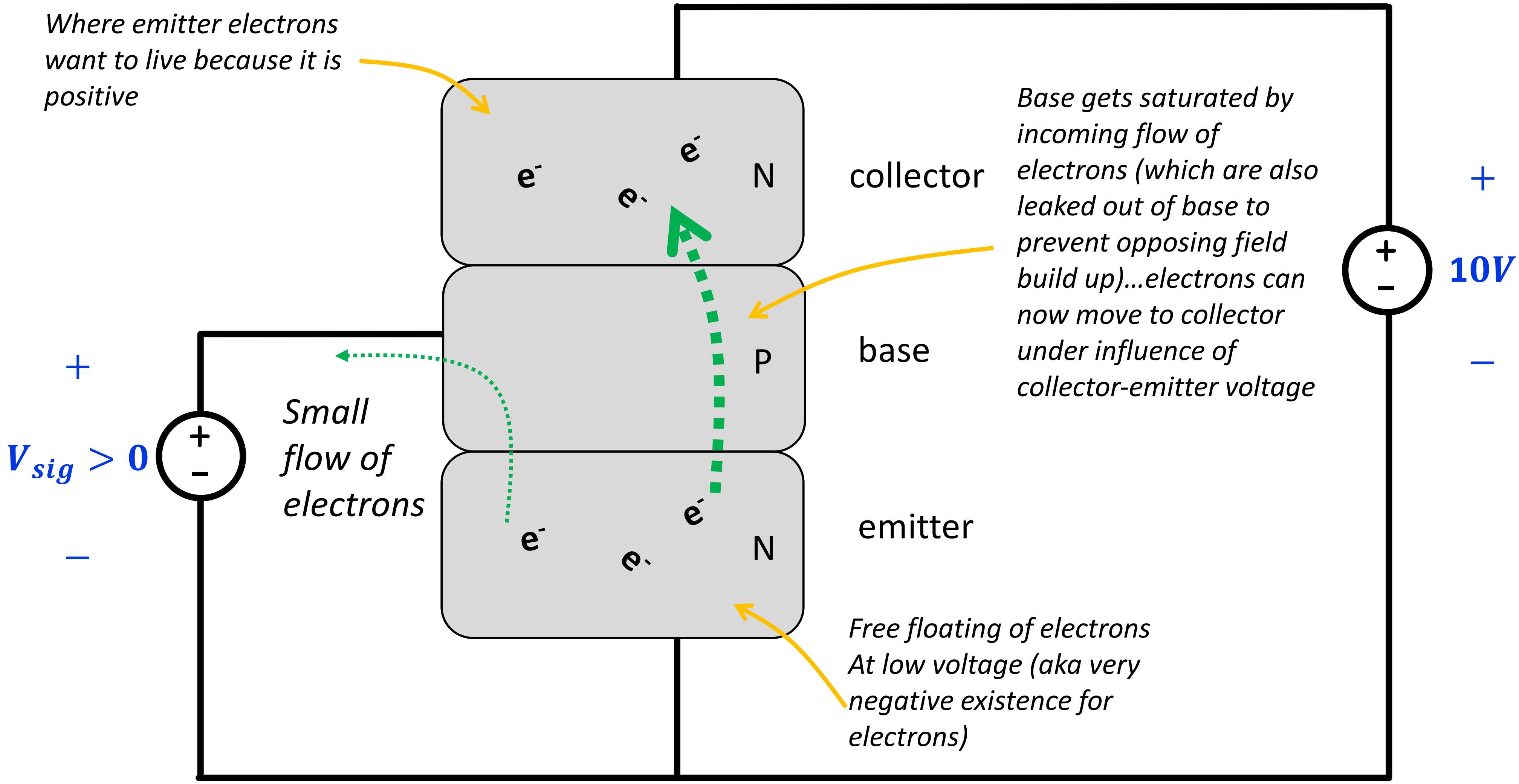
Why this nomenclature?...consider NPN transistor:

- Worked off the charge carriers being manipulated



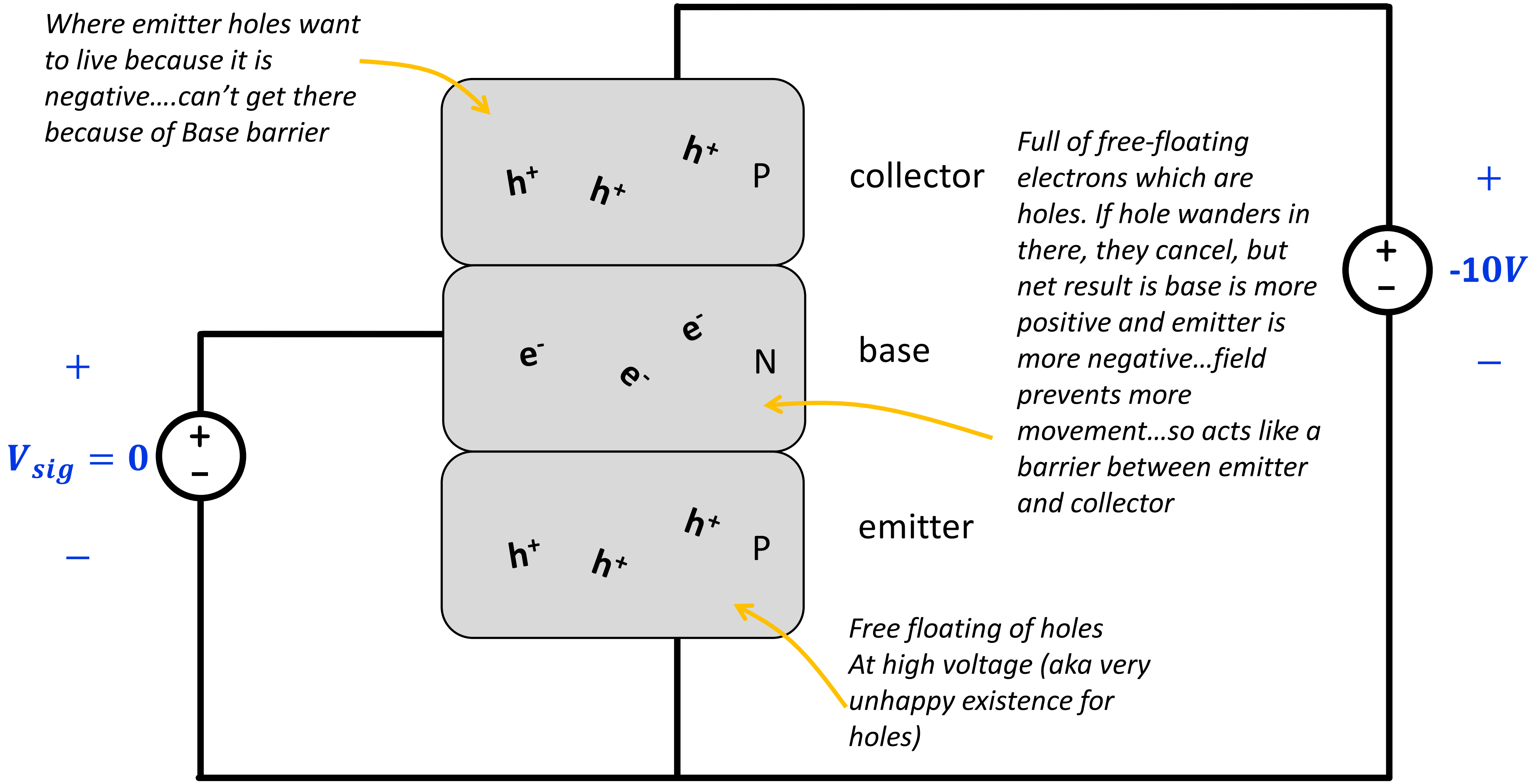
Let a little current flow into base (allow a few electrons to escape there…)

- No buildup in base-emitter



Same But Opposite with PNP

- Worked off the charge carriers being manipulated



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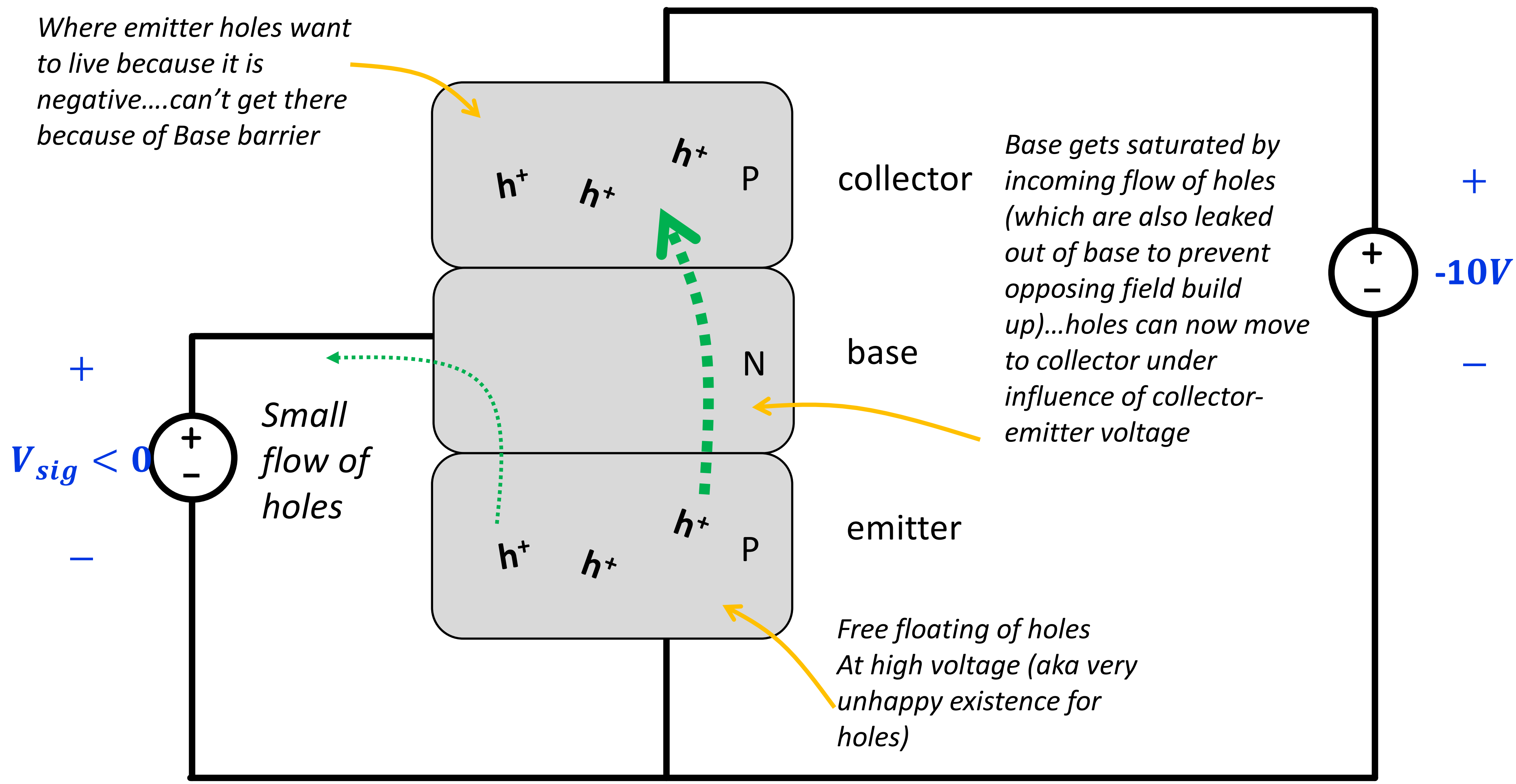
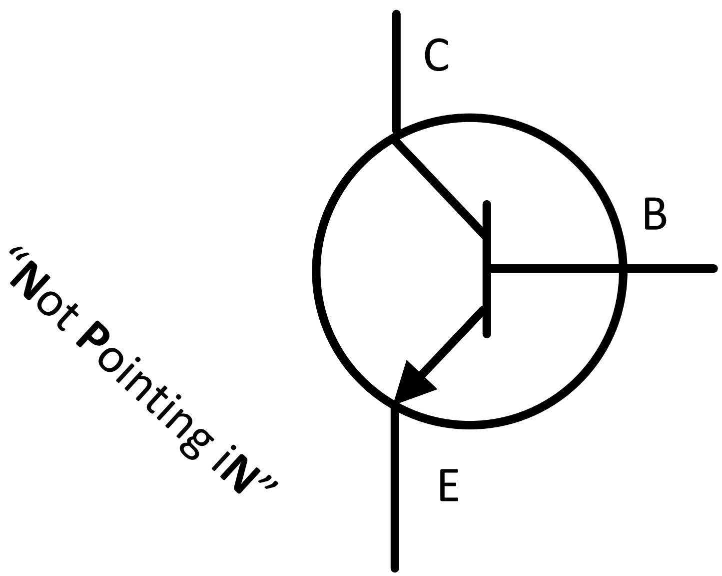


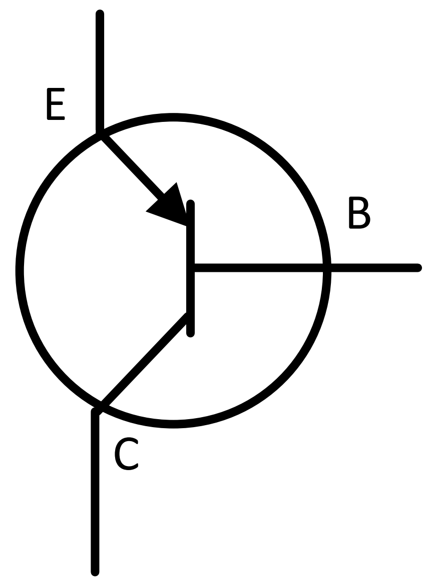
Second Big Departure: Two Types of Transistors

- With transistors by swapping the semiconductor "type" order you could get two different complementary devices:
  - NPN where you modulate the flow of electrons
  - PNP where you modulate the flow of holes

NPN:



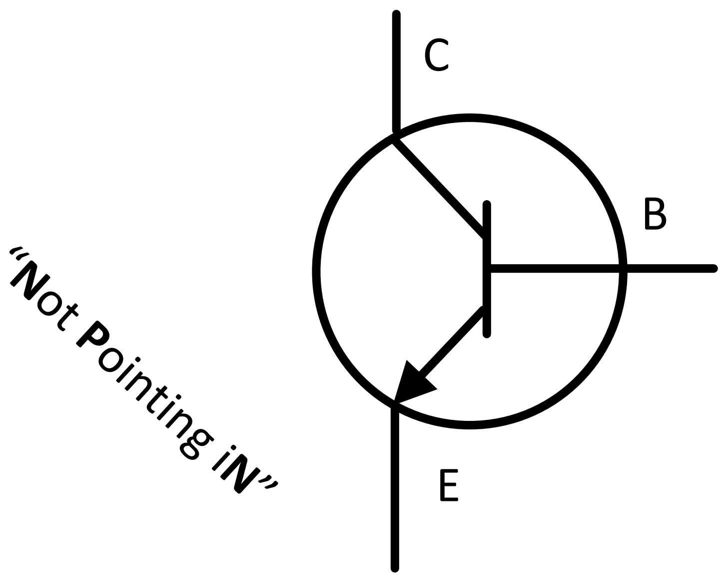
PNP:



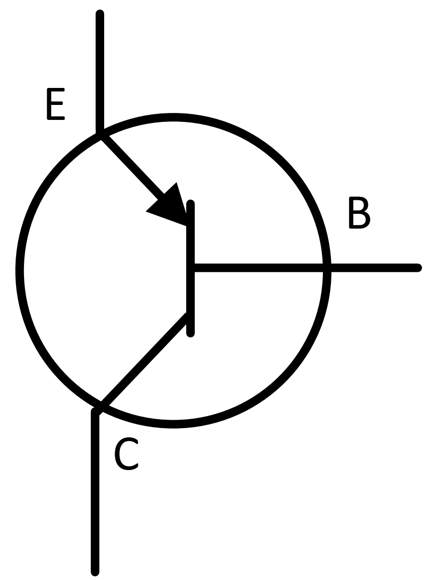
The Result of these two devices:

- NPN: Collector current flows when base current is positive!
- PNP: Collector current flows when base current is negative!

NPN:

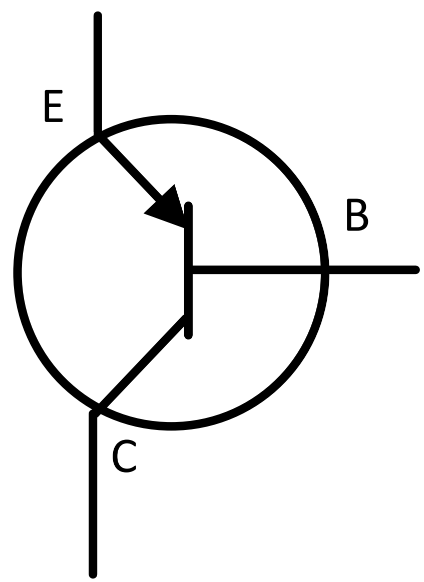


PNP:



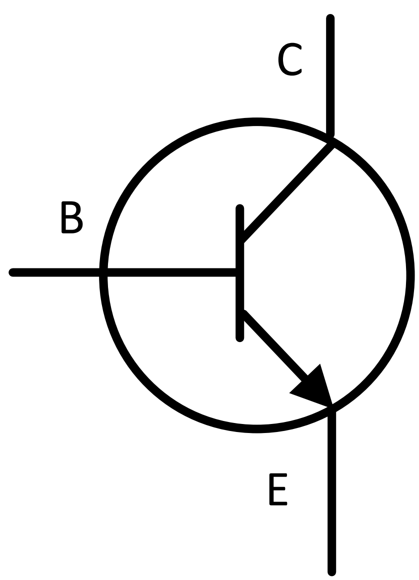
Early Transistors

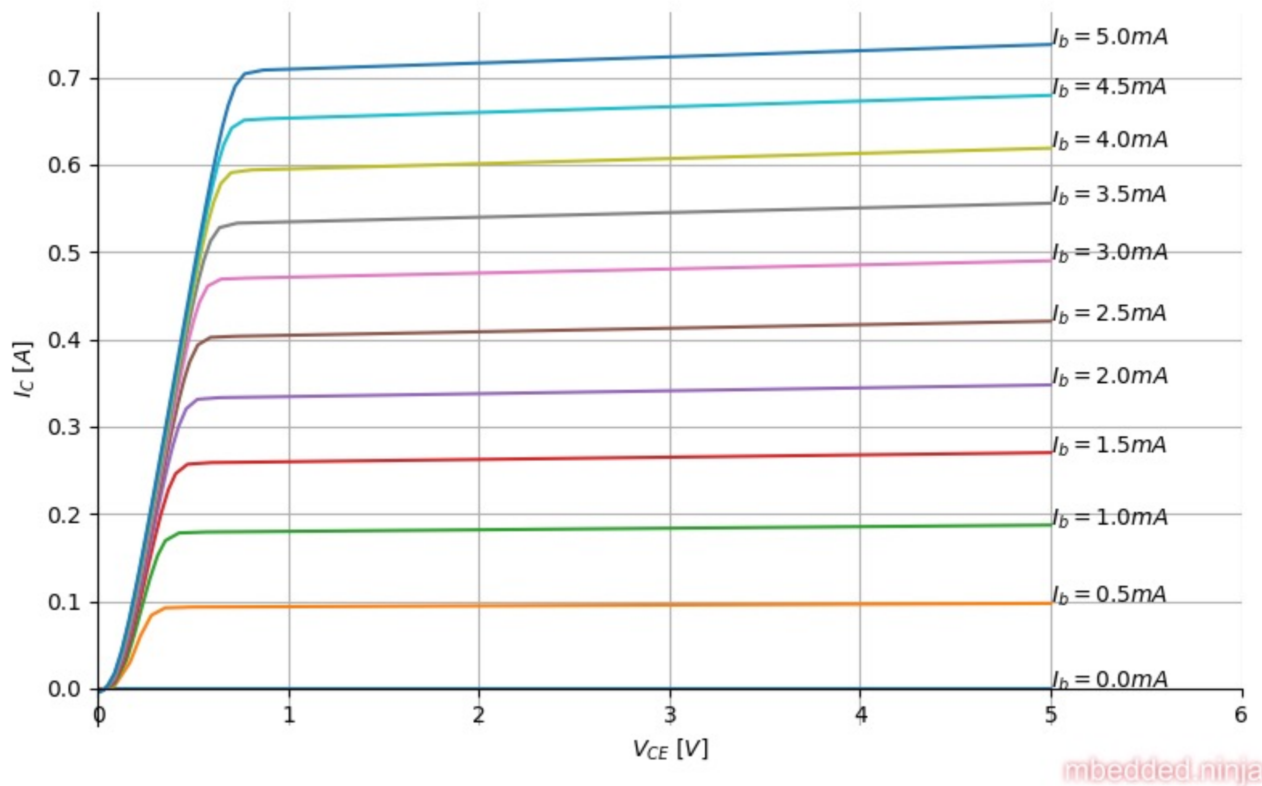
- The majority of early germanium transistors were PNP-based.
  - Based on a number of manufacturing limitations with the different dopants
- Germanium was easier to purify early on so it was used a lot at first.
- NPN transistors did exist but never became common-place until mid 1950s
- Silicon proved to be a far better:
  - Band-gap voltage of 0.7V rather than 0.2V for germanium, so could make a better insulator
  - Had better thermal properties
  - Just took a lot longer to get the material handling of it under control



Transistors were three-terminal devices…just like triodes/tetrodes/pentodes

NPN:





https://blog.mbedded.ninja/electronics/components/transistors/bipolar-junction-transistors-bjts/output-transfer-characteristics-microcap-sim/plot.png

Semiconductor Device Physics

- The "Transistors" Service Training Course written by *Bob Widlar* in 1960 does a fantastic job of showing how transistors work without necessarily disappearing too much into physics
- I've included on course website

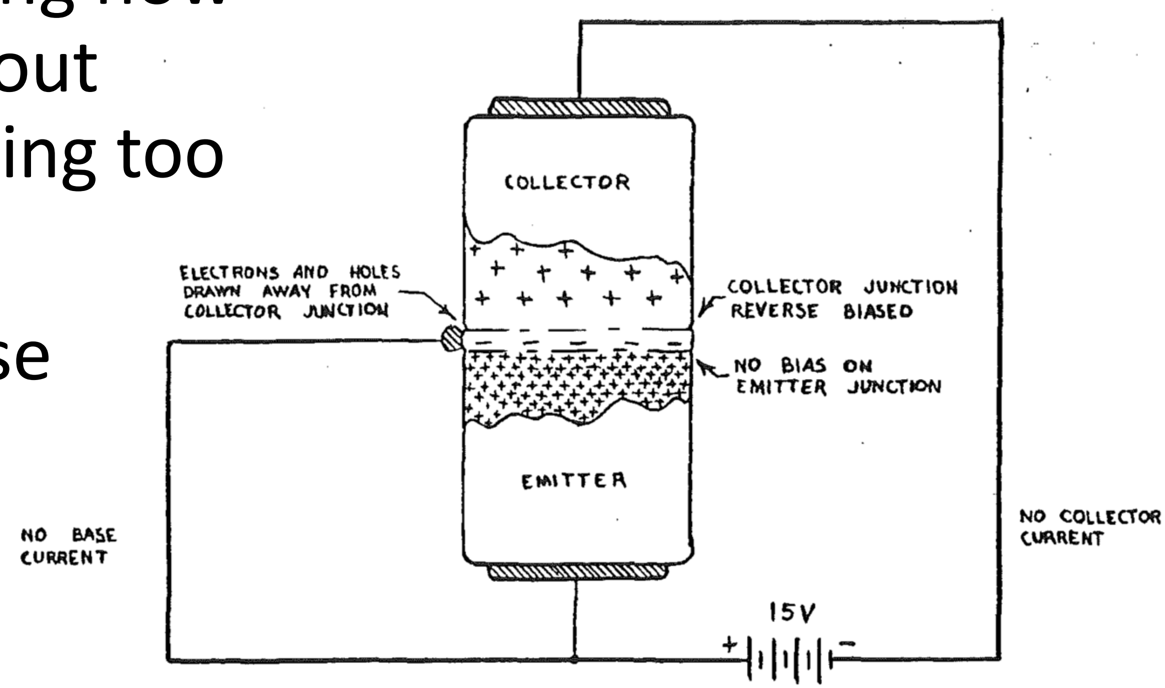
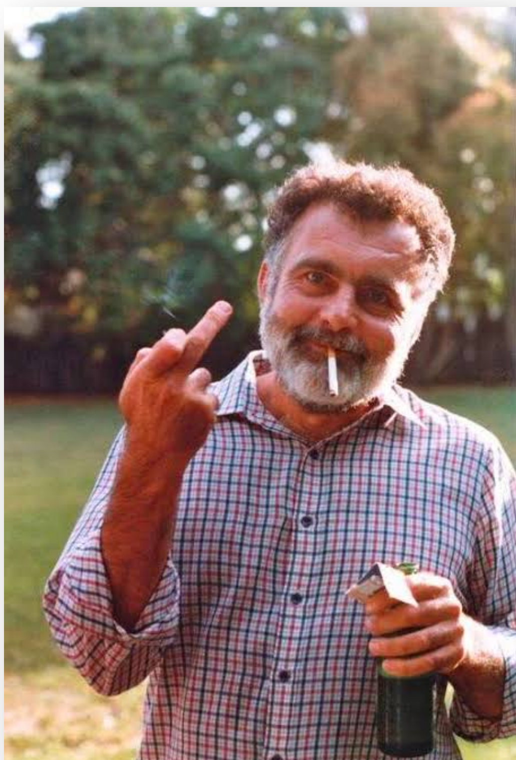


Figure 1.7. PNP Transistor in Nonconducting State.

Aside: Bob Widlar

- Early Analog Transistor Engineer
- Weird Guy
- Designed first real integrated op amp and many other famous circuits



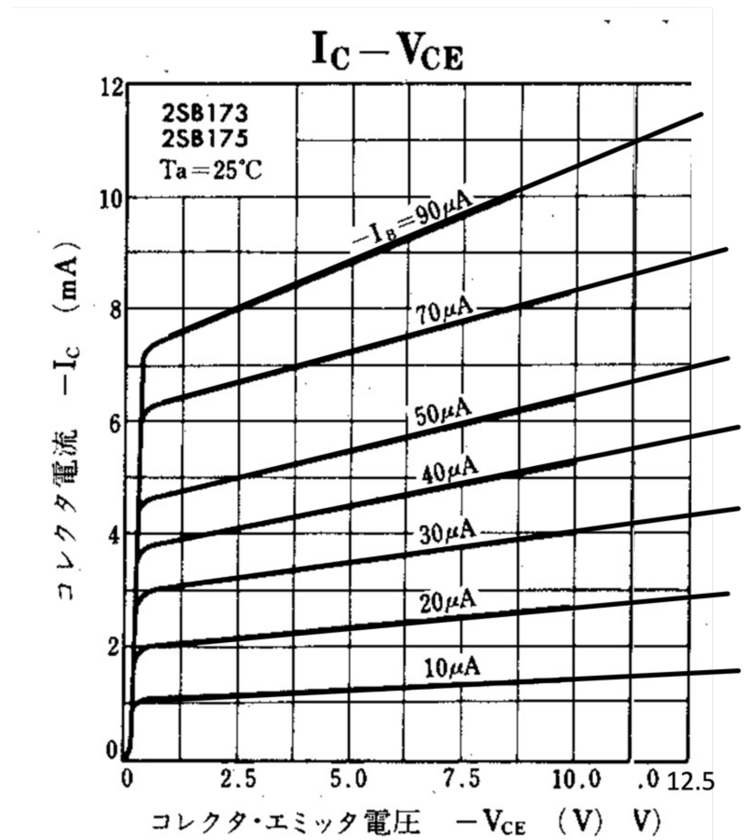
Bob Widlar, Everybody

"A Fairchild researcher trained a frog to jump at the sound of a bell. The researcher measured the distance the frog would jump, then removed the frog's legs and rang the bell again. The frog did not move, thus proving the Fairchild R&D group hypothesis that removing a frog's legs deafens the animal."

Robert J. Widlar,
describing Fairchild's R&D group in 1967

Third Big Departure

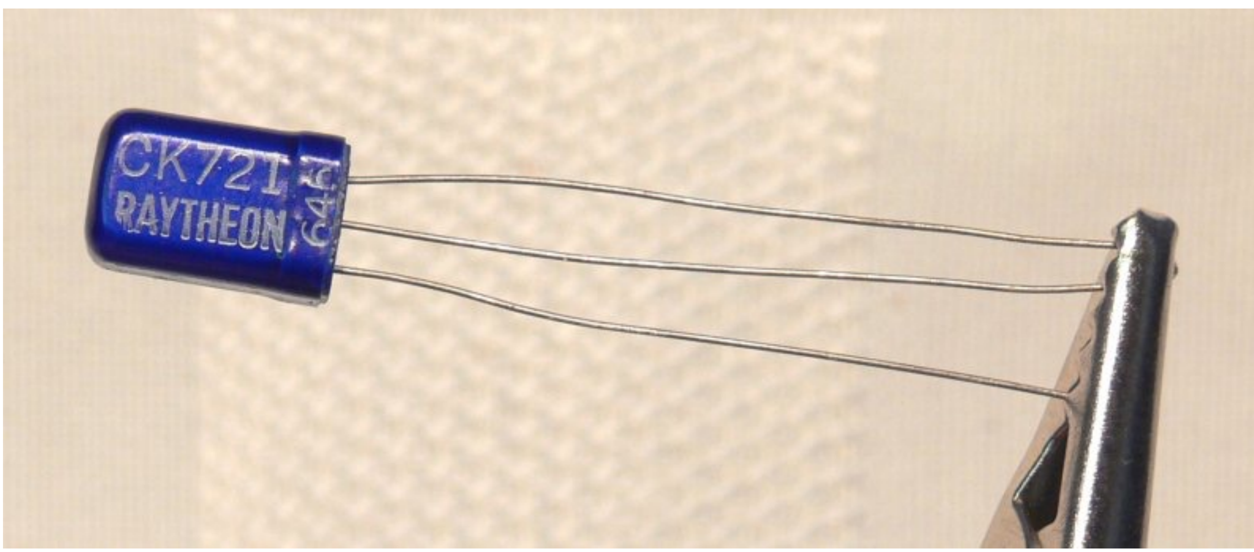
- Transistors could do what we needed (give us a juicy pentode-like I-V set of curves) all while running at very low voltages!
- Also didn't need to be heated
  - Tubes generated free carriers via thermionic emission which needed hungry hungry heaters
  - Transistors had free carriers because of material science and the doping of semiconductors



Look 12.5V!!!

Early Transistors

- Development Happened Fast!
- First transistor: ~Dec 23, 1947 (75 years ago)
- First good junction transistor available for non-government people was CK721 (Raytheon)…around 1953…cost about 7 dollars

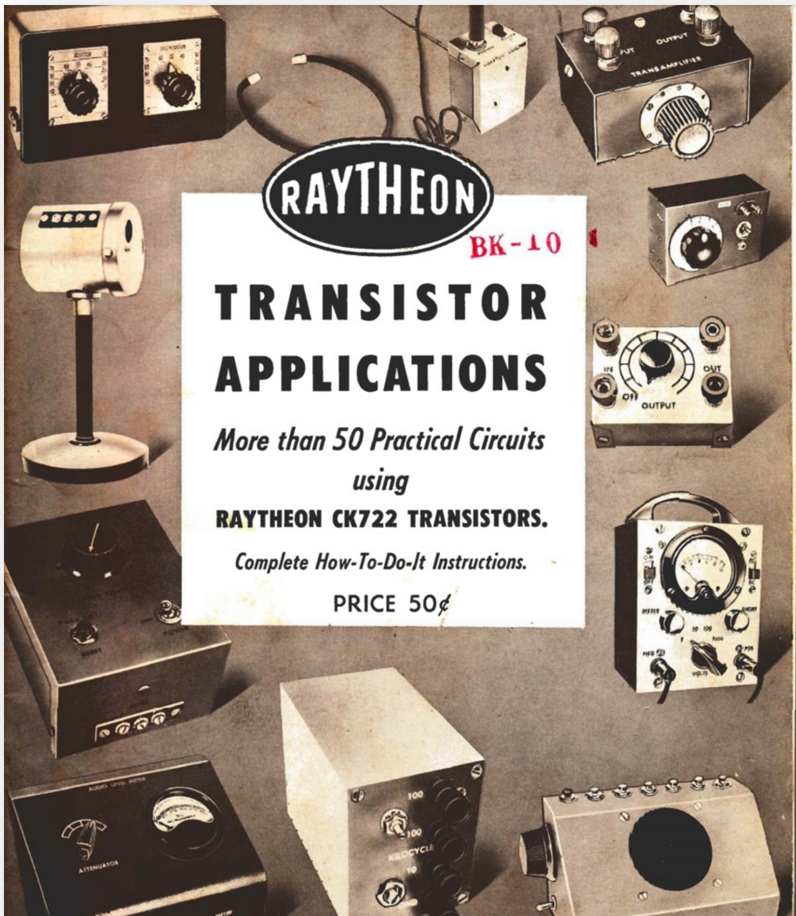


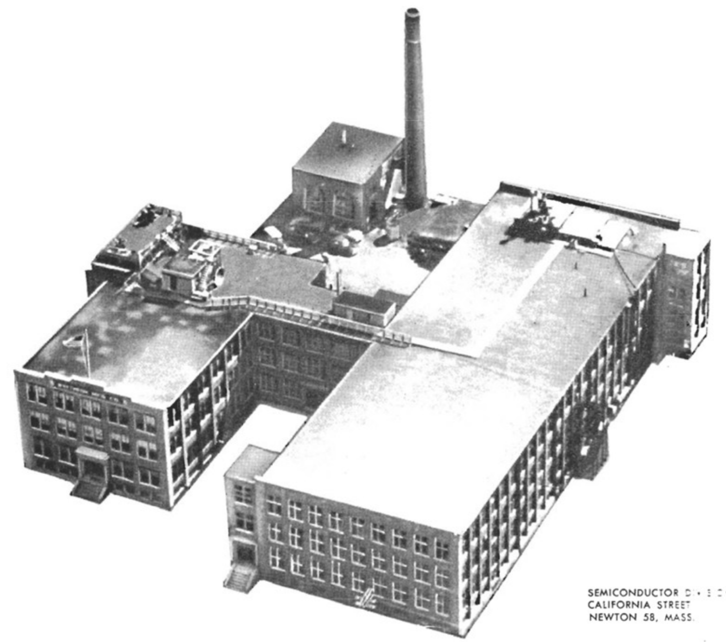
So as a circuit engineer in the early 1950s…

- Found yourself in a rapidly changing field where:
  - The amplifying devices were different (current vs. voltage based control)
  - The primary new type worked opposite the way you knew (tubes were N-type…most transistors were P-type)
  - Voltage ranges for regular operation were much smaller!
- Manufacturers Needed to Show Users How to Build with Transistors and provided technical manuals and lists of circuits to build along with discussions about how to work with them!

Early Transistor Manufacturers

- Tons of early transistor manufacturers.
- Raytheon was a big early one





THE HOME OF RAYTHEON TRANSISTORS

This multimillion dollar plant is the largest in the world devoted exclusively to the production of semiconductors. Three times the size of former facilities it meets the demand for Raytheon Transistors brought about by Raytheon leadership in transistor design and development.

Raytheon produced the first commercial transistors for hearing aids — the transistors that have revolutionized the hearing aid industry.

In the computer industry and in the newest and finest portable and automobile radios the new Raytheon RF Transistors are proving equally valuable and important.

Today, there are several million Raytheon Transistors in use —

More In Use Than All Other Makes Combined

Lots of Really Cool Simple Designs

AUDIO AMPLIFIERS

By **CHARLES W. MARTEL**
Raytheon Manufacturing Company

age crystal mike will give at least 10 db less power than a dynamic microphone and, in addition all crystal microphones have high impedances which will not match the relatively low input impedance of the grounded emitter CK722 unless coupled through a step-down transformer. The circuit will be identical to that of Fig. 3C except that the transformer primary impedance should be as high as possible (several hundred thousand ohms) and the secondary impedance should be about 1000 ohms. An intercom transformer of the type used to couple the voice coil of a loudspeaker microphone to the input tube grid may be used "in reverse" to obtain a reasonably good impedance match.

With the input circuit determined, the next step is to add transistor stages to obtain the desired gain. The user of this amplifier will listen-in

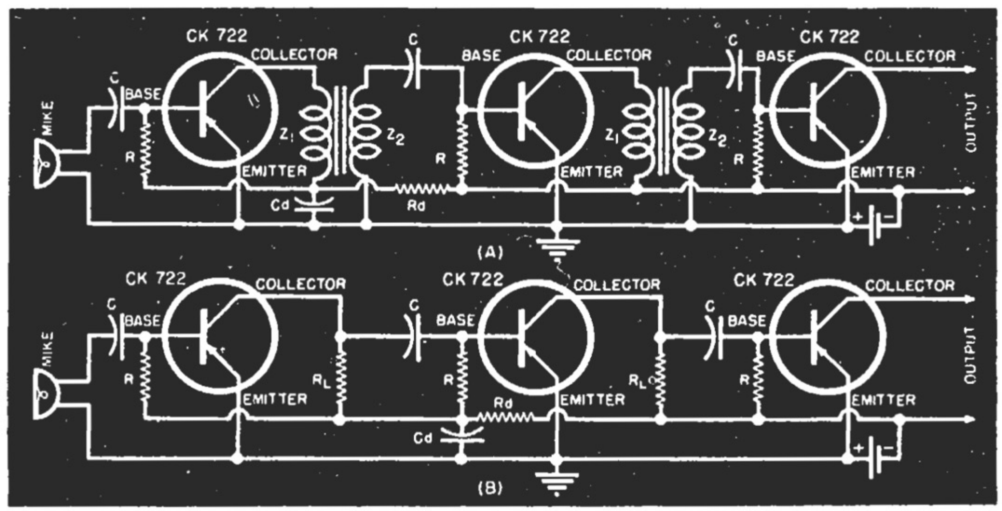
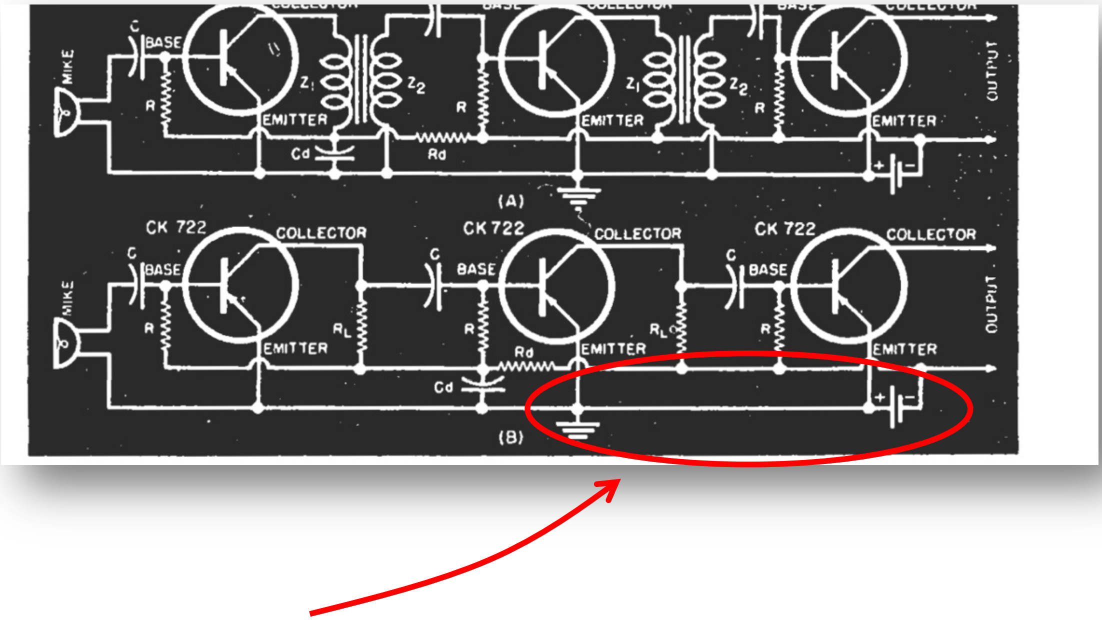


Fig. 2. (A) Transformer-coupled and (B) resistance-coupled amplifiers using transistors.

a voltage at the collector because of

Lots of Really Cool Simple Designs

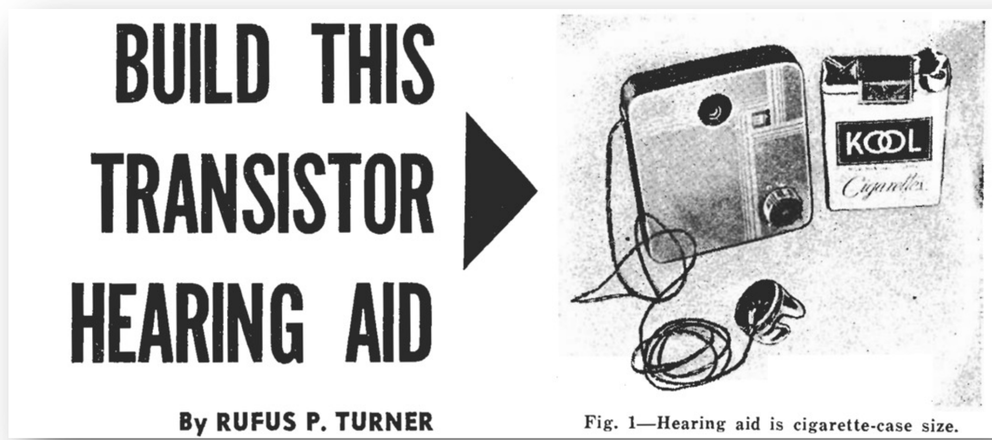
- They'd sometimes do weird things to make the tube-to-transistor transition be easier.
- Many PNP-transistor circuits have their ground being the high voltage of the circuit!
- This is to keep the same emitter/cathode-at-bottom pattern consistent



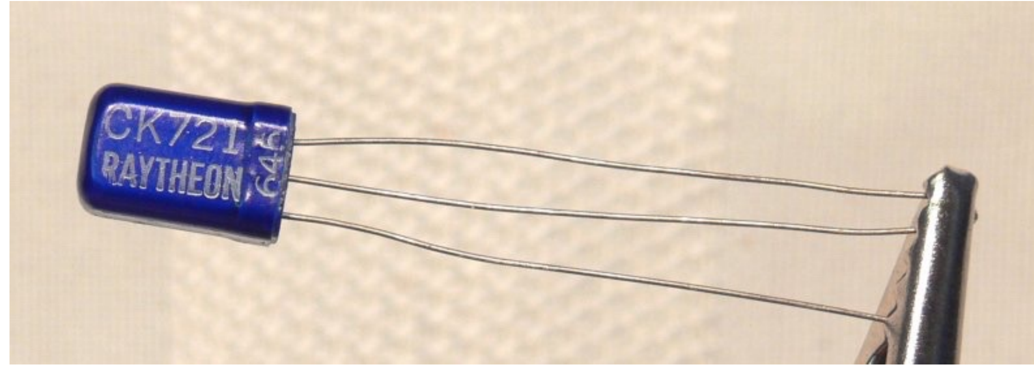
Early Killer-Apps for Transistors!

- Hearing Aids and Nuclear missiles were the first two big applications.
- Want a tiny battery powered hearing aid
- Want your detonator to be very robust on an ICBM

First electronic transistorized hearing aid
Used several CK718 transistors



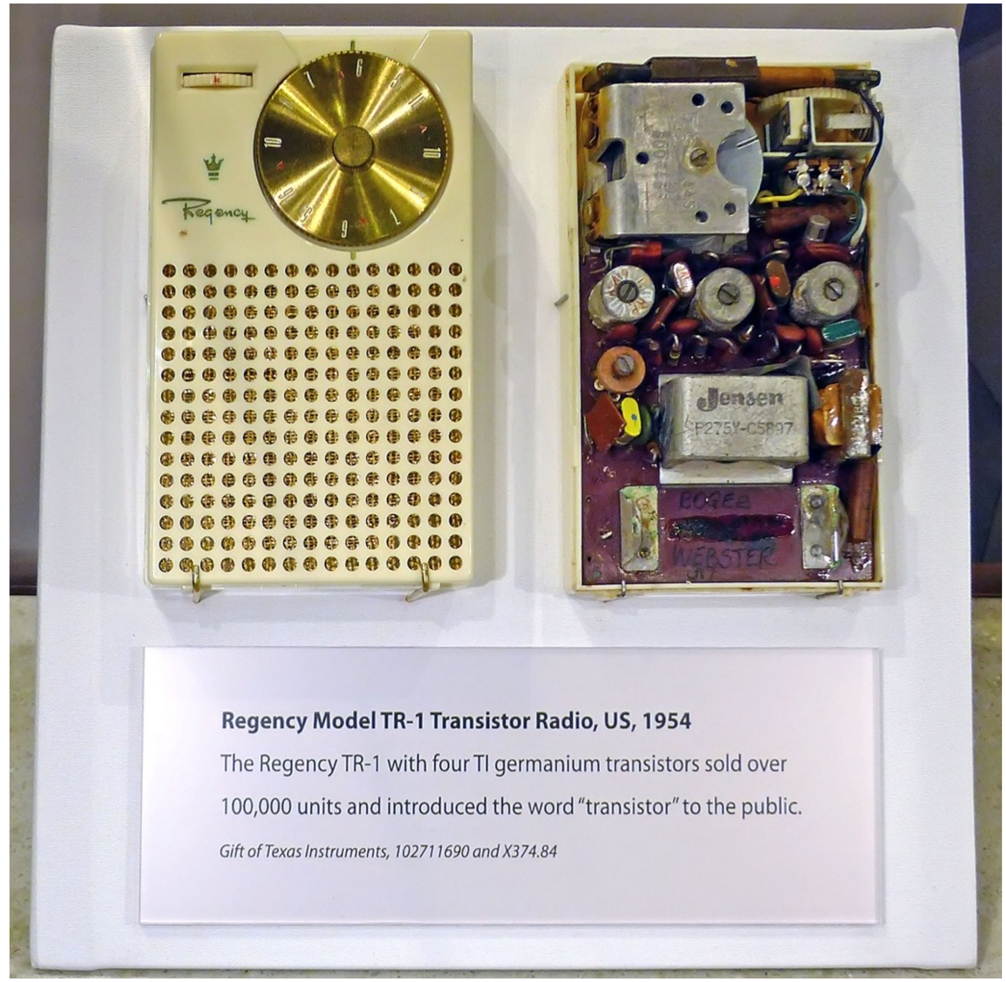
CK721/722



- Hearing aid transistor rejects that didn't have as much gain were classified as either CK721 or CK722 depending on actual gain and then sold at different price points to general population
- These formed the basis of startups and lots of new circuits and ideas. A lot of the IC designers that showed up over the next few decades got their start with these parts.

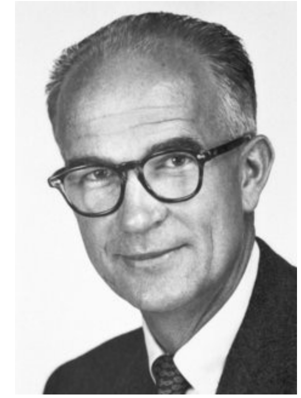
Regency TR-1

- First Transistor Radio
- Made by Texas Instruments in 1954
- Really expensive at time compared to vacuum tube radios ($49.95)…about $443 in today's dollars
- Meant to be personal



http://www.regencytr1.com/

Shockley TRANSISTOR



- Mid 50’s Shockley decided to found his own company called Shockley Semiconductor in Mountainview, CA mainly for family reasons (sick mother nearby).
- Was dumpy area then. Land was cheap and mostly orchards
- Hired a bunch of smart people to work on transistors but also go really obsessed with what would eventually become the thyristor

Shockley

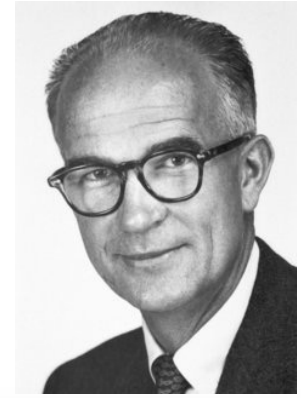
- NOT a good boss…yelled a lot, fired people, made people take lie detector tests…changed his mind all the time…really messy
- bunch of engineers got fed up and quit, founded their own company with support from Fairchild Corporation!
- These eight became known as the “Fairchild Eight” or the “Traitorous Eight” by Shockley

- Very early Conglomerate Company. Had:
  - Aircraft Division (got their start)
  - Camera Division
  - Scientific Instrumentation Division
  - Weapons Division: ArmaLite…invented AR-15 and variants then sold that off
  - Semiconductor Division: Fairchild Semiconductor
  - And many others…did a lot of seed funding

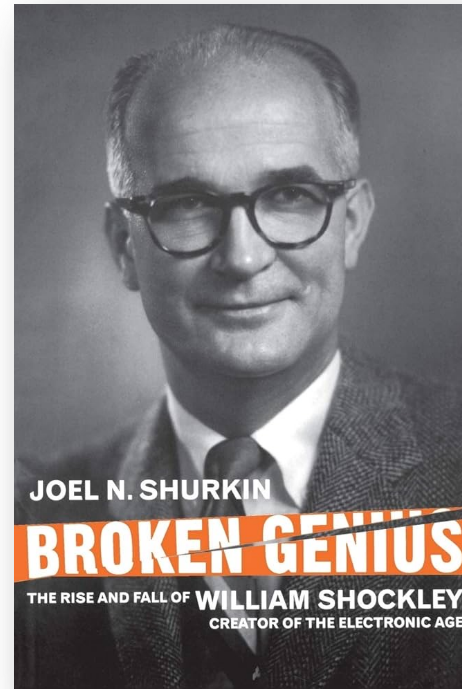
Fairchild Semiconductors

- Gordon Moore and Bob Noyce among the founders of Fairchild
- After Fairchild was success, they left to found Integrated Electronics…which was shortened to Intel
- Noyce also co-invented integrated circuit at same time as Jack Kilby who was at Texas Instruments
- TI was the other big early semiconductor company…their big angle was moving to Silicon early

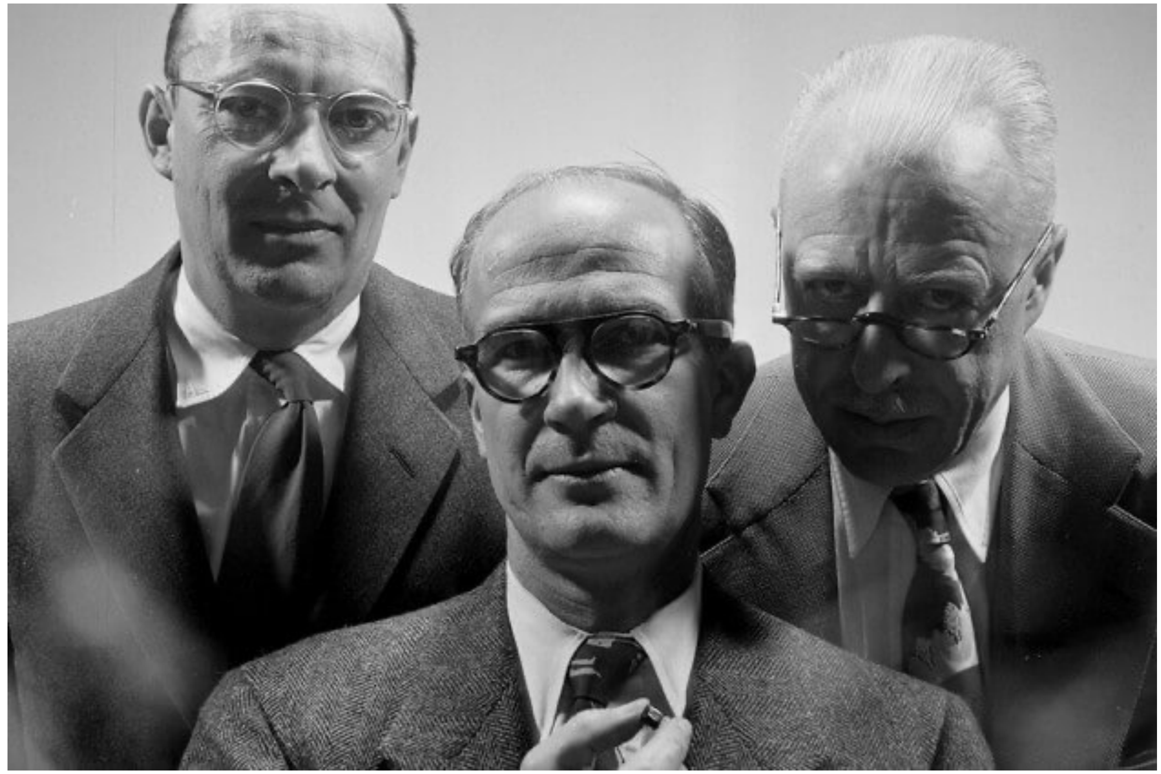
Shockley



- Shockley Semiconductor failed
- But all the people he pissed off stayed around in the Valley area and basically spawned pretty much everything. Early Apple and Microsoft people came from Intel, then people from those companies were involved with Google, Facebook, etc…
- Shockley became a professor at Stanford
- He was also kinda a racist and into eugenics and alienated a lot of people and died mostly estranged from his family
- Joel Shurkin's *Broken Genius* is a good read on him if you want.



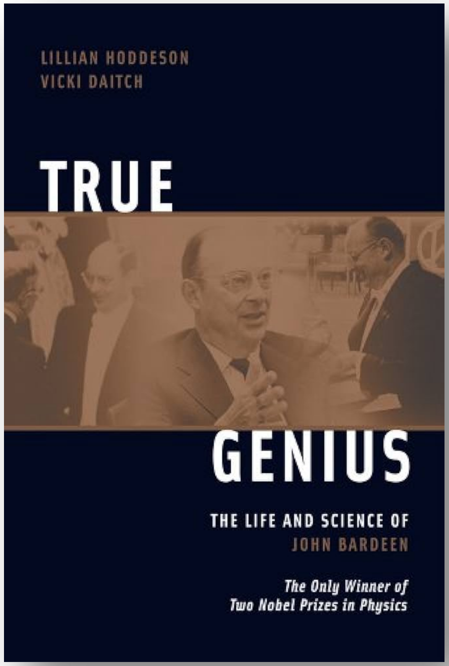
Transistor Trio in Life Photoshoot in late 50's when they won their Nobel



https://hotcore.info/babki/william-shockley-john-bardeen-and-walter-brattain.htm

Bardeen vs. Shockley

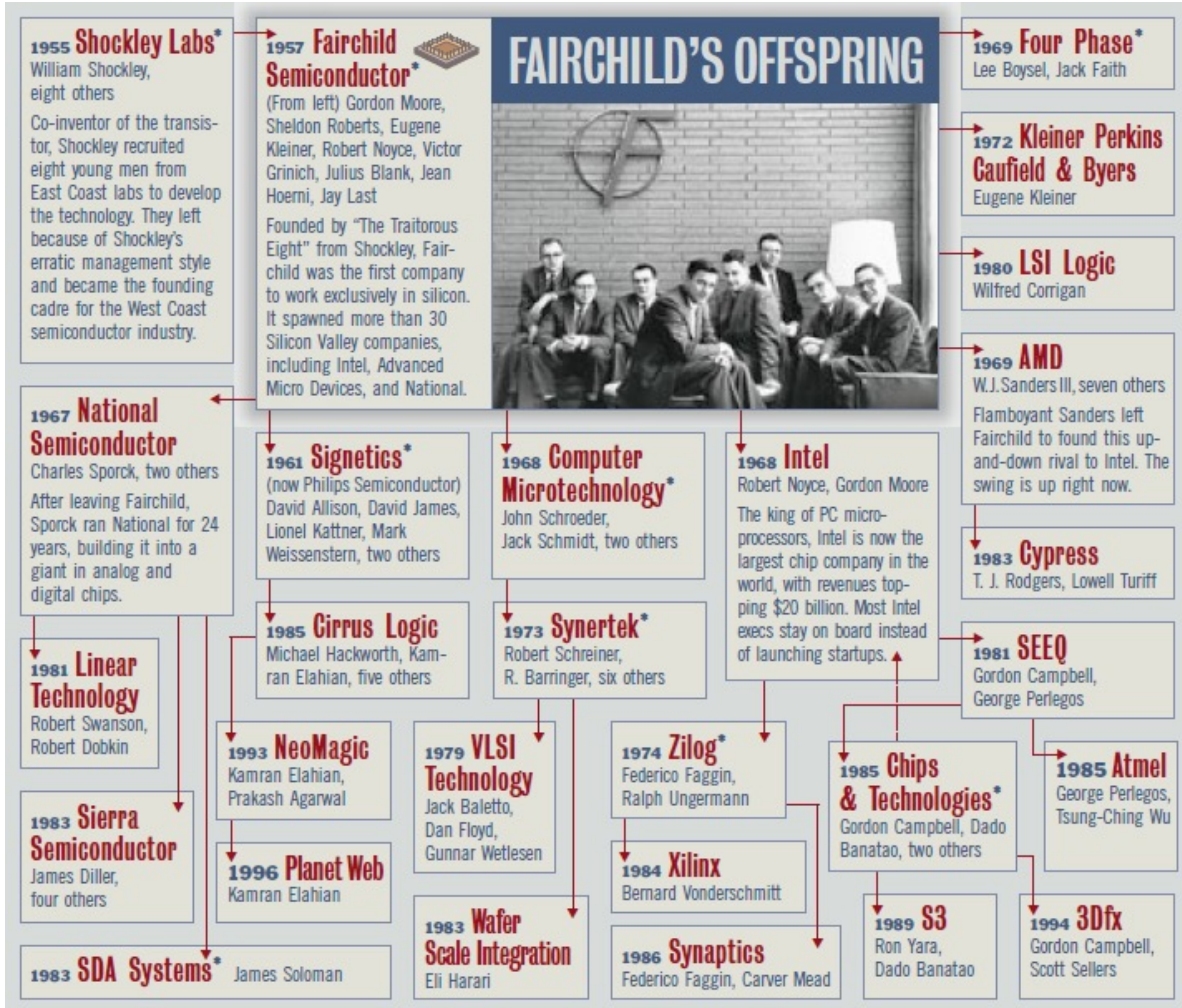
- Hoddeson and Daitch Wrote a bio of Bardeen *True Genius* also…kinda funny to contrast that title to Shockley’s *Broken Genius*
- No bio on Brattain that I know of, but by all accounts, he was a nice dude.



Family Tree

The rest is history in a sense. Direct line from Shockley/Fairchild to almost <u>every</u> modern company

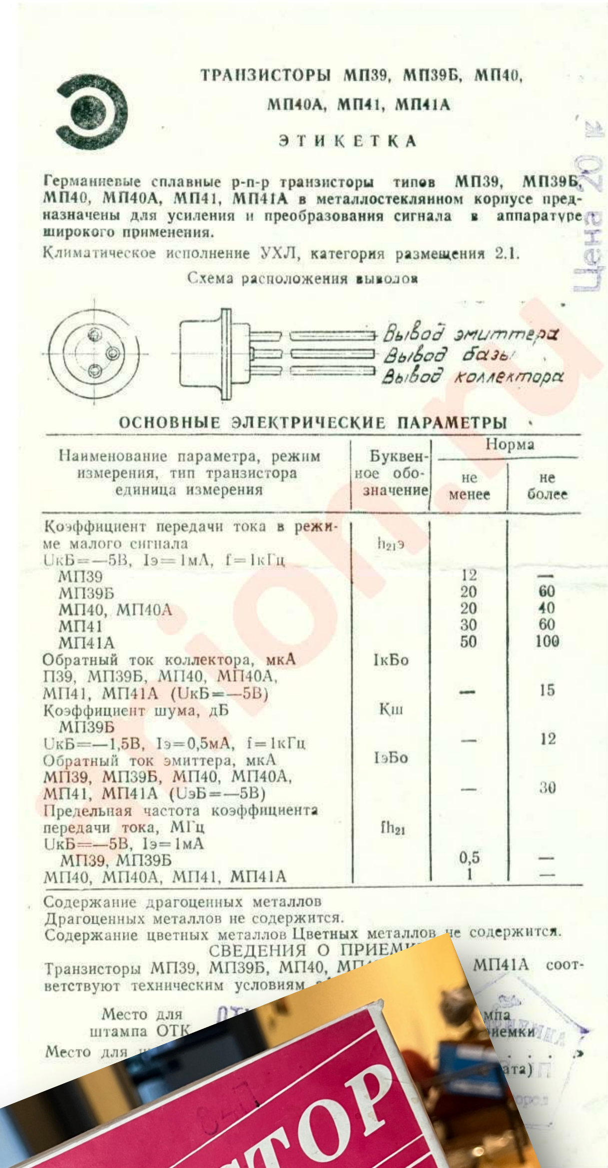
If not through direct engineering, then through investing, advisorial roles, etc…



https://daviddhovey.files.wordpress.com/2010/09/blog101.png

Lab 04

- Build a halfway-decent Germanium Audio Amplifier
- For transistors we'll use two different types:
  - МП41: preamplifier and phase-splitter
  - МП20: power amplifier
- Both are PNP Germanium-type transistors from the Soviet Union



ТРАНЗИСТОРЫ МП39, МП39Б, МП40, МП40А, МП41, МП41А

ЭТИКЕТКА

Германиевые сплавные p-n-p транзисторы типов МП39, МП39Б, МП40, МП40А, МП41, МП41А в металлостеклянном корпусе предназначены для усиления и преобразования сигнала в аппаратуре широкого применения.

Климатическое исполнение УХЛ, категория размещения 2.1.

Схема расположения выводов

ОСНОВНЫЕ ЭЛЕКТРИЧЕСКИЕ ПАРАМЕТРЫ

Наименование параметра, режим измерения, тип транзистора единица измерения	Буквенное обозначение	Норма не менее	Норма не более
Коэффициент передачи тока в режиме малого сигнала UкБ=—5В, Iэ=1мА, f=1кГц	h21э		
МП39		12	—
МП39Б		20	60
МП40, МП40А		20	40
МП41		30	60
МП41А		50	100
Обратный ток коллектора, мкА П39, МП39Б, МП40, МП40А, МП41, МП41А (UкБ=—5В)	IкБо	—	15
Коэффициент шума, дБ МП39Б UкБ=—1,5В, Iэ=0,5мА, f=1кГц	Кш	—	12
Обратный ток эмиттера, мкА МП39, МП39Б, МП40, МП40А, МП41, МП41А (UэБ=—5В)	IэБо	—	30
Предельная частота коэффициента передачи тока, МГц UкБ=—5В, Iэ=1мА	fh21		
МП39, МП39Б		0,5	—
МП40, МП40А, МП41, МП41А		1	—

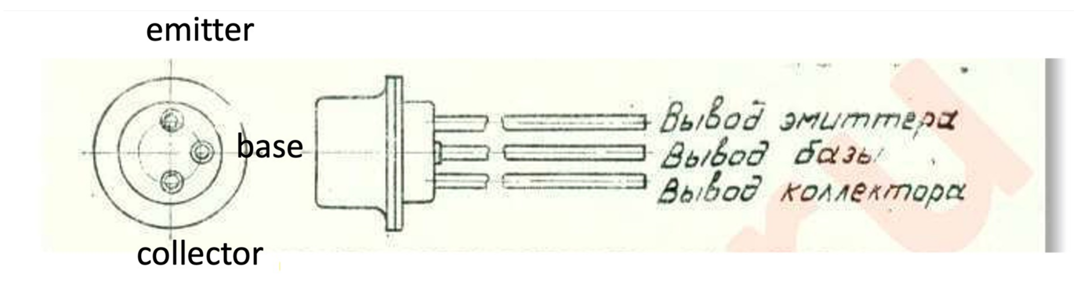
Содержание драгоценных металлов
Драгоценных металлов не содержится.
Содержание цветных металлов Цветных металлов не содержится.

СВЕДЕНИЯ О ПРИЕМ

Транзисторы МП39, МП39Б, МП40, МП МП41А соответствуют техническим условиям

Место для штампа ОТК

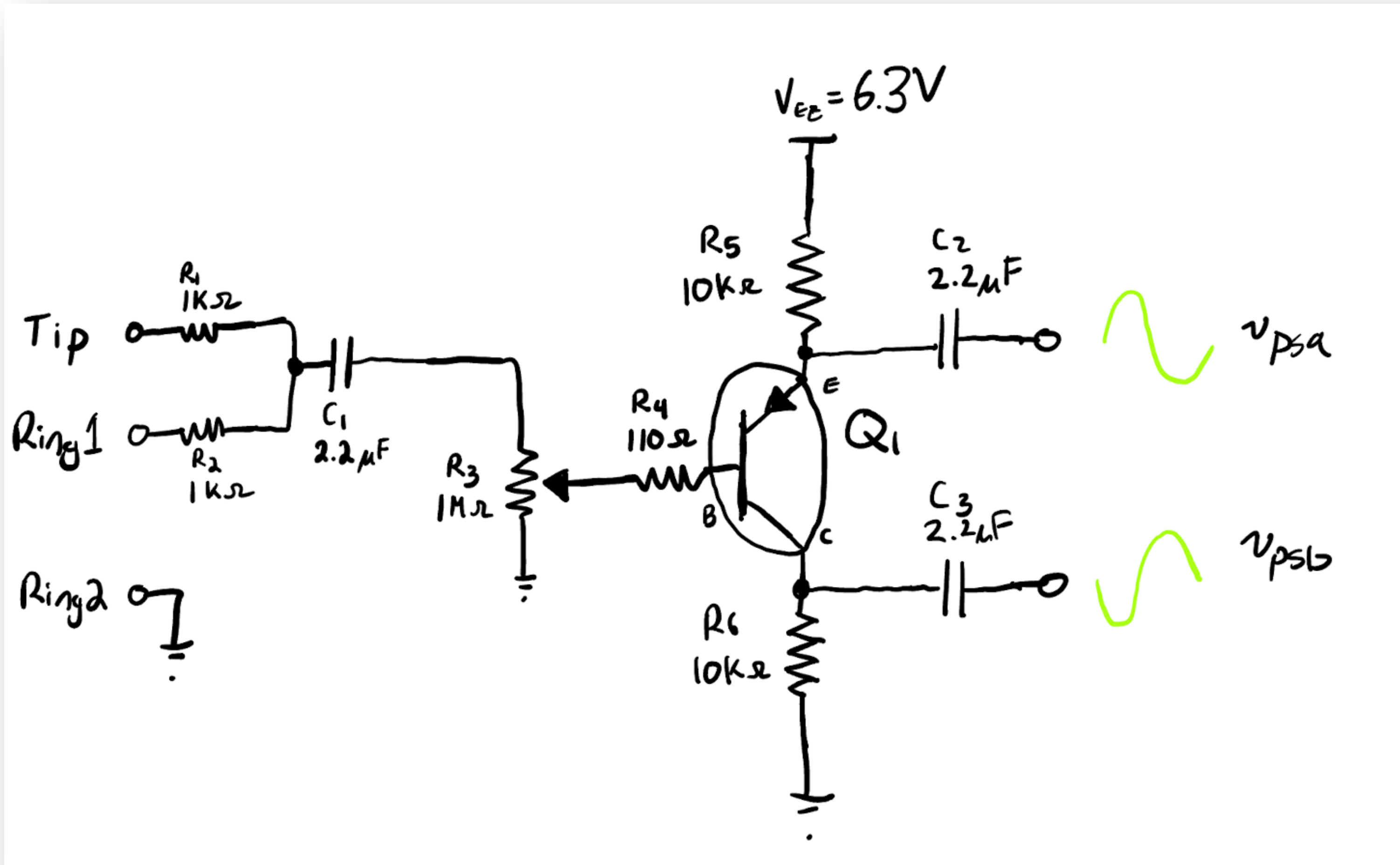
Место для



Preamplifier and Phase Splitter

- A little voltage gain and create two out-of-phase signals

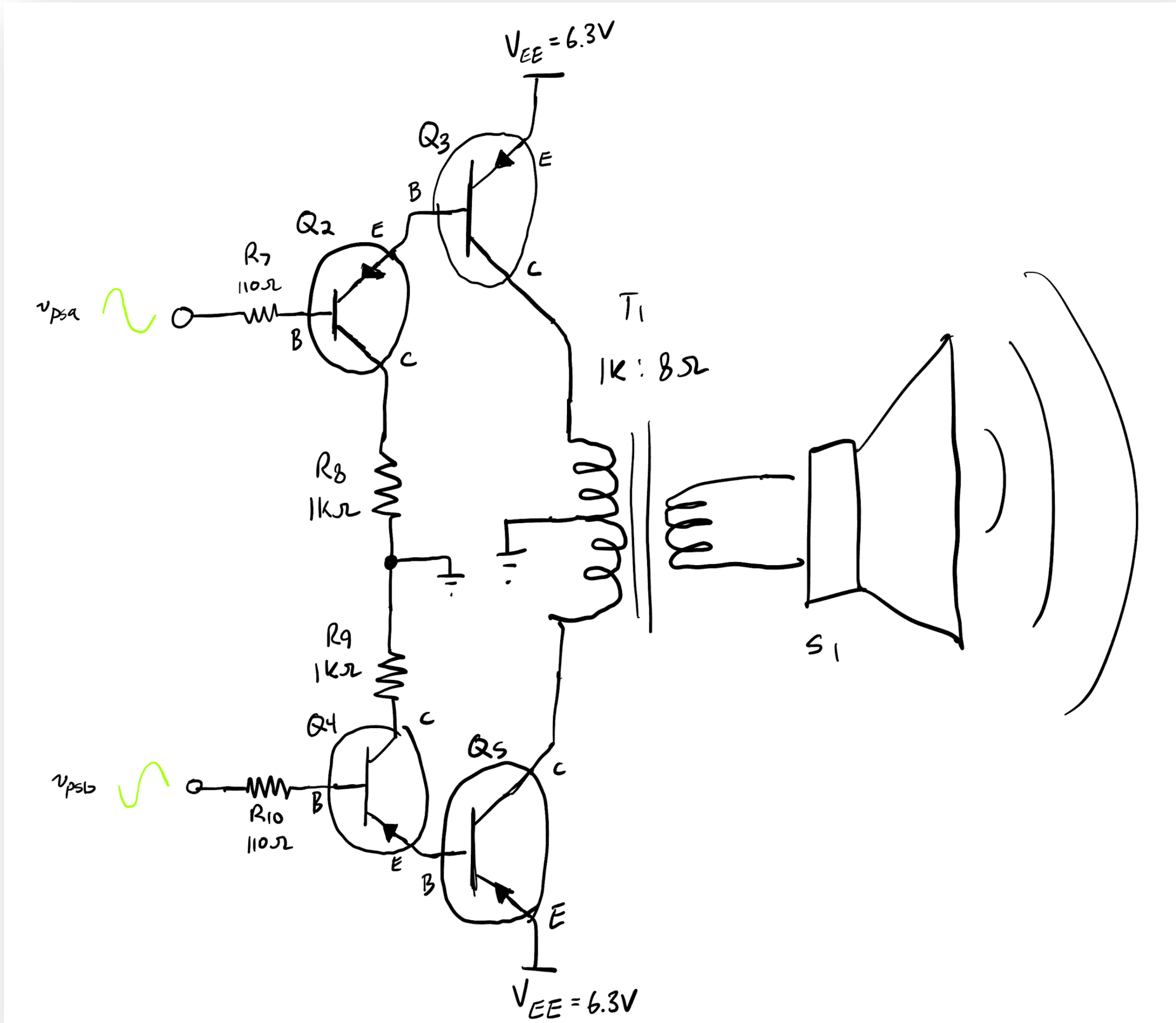
Q_1= МП41



Power Amplifier

- Use Darlington Pair Configurations to Drive Amplifier in Push-Pull Format:

$Q_{2,4}$= МП41
$Q_{3,5}$= МП20



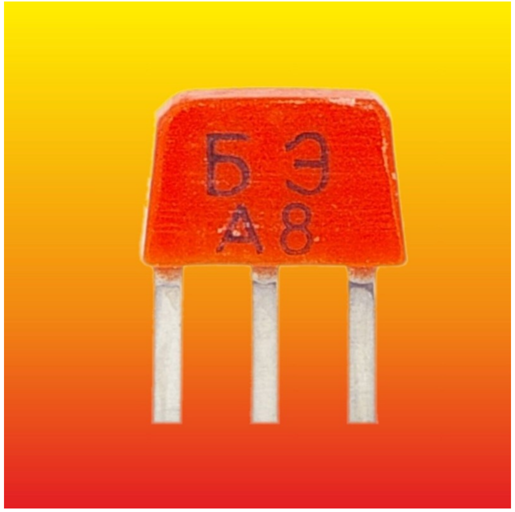
Why *Not* Western Transistors?

- Is complicated…basically very hard to get Western transistors from the era
- Early transistors were not super reliable. Broke sometimes as often as vacuum tubes
- Also very variable (make a bunch, pick your best, chuck the rest).
- Also tech updated crazy fast in the West.
  - By 1957 (ten years after transistor invention), TI was making silicon NPN transistors not that different from “modern” designs
  - Transistors weren’t made in large volumes since most things that needed to be reliable kept using tubes until very early 1960’s
- Also US did not archive stuff…many old circuits and stocks were discarded before they were seen as “history”

But Why *Soviet* Transistors?

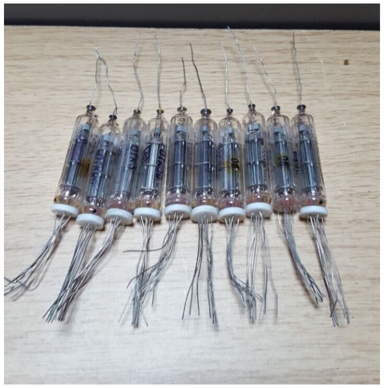
- Is complicated…Soviet Union lagged the West in terms of electronics technology by about ~10 years.
- When Western firms were starting to tame Silicon, Soviet scientists were just starting to get transistors in germanium to work at all (mid 50's)
- Silicon proved very difficult and expensive to get working…Soviets didn't have decent silicon transistors until early 1970's

KT315…very late 1960's…~about ten years after equivalent US NPN silicon transistors



Why Soviet Transistors?

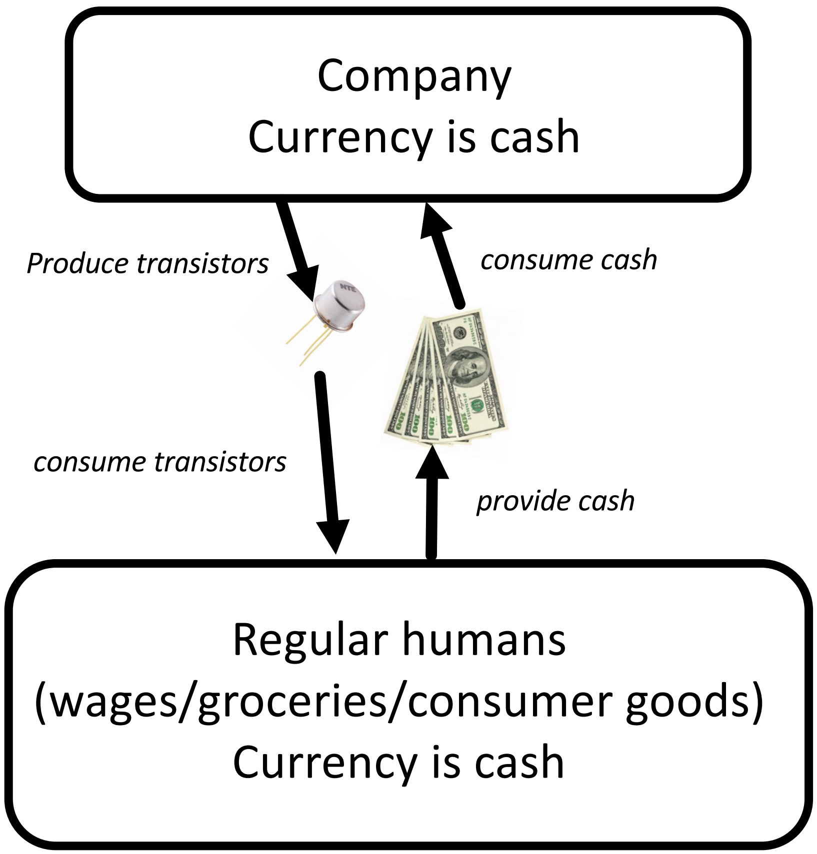
- The Soviet Union did a lot of stuff: huge military, space technology program, lots of science, so they needed good amplifying devices.
- Space race, development of nuclear arsenal, massive military export/expansion all happened in their Germanium transistor window so a lot of legacy equipment kept using them even into the 90s
- Kept perfecting Germanium and vacuum tubes long after Western companies had started to move on.



Soviet sub-mini tubes from 1950s

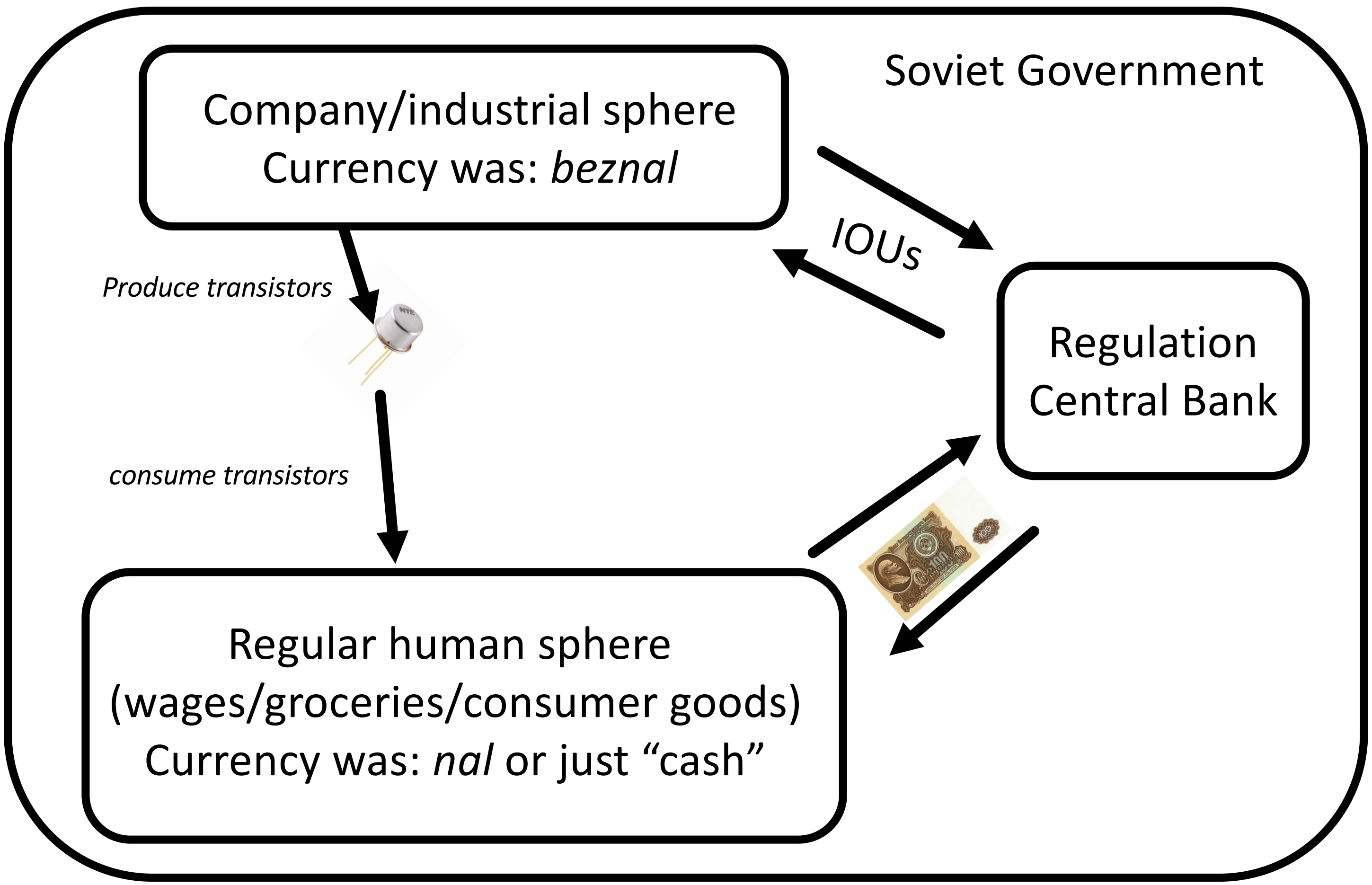
Modern "Western" Economic System

- While money may exist in several "forms", the different forms are largely fluid with one another.



Soviet Economic System

- Soviet economy was two disconnected spheres with essentially two disconnected forms of currency



The Result

- Feedback loop regarding many technologies such as tubes but also early transistor variants was essentially disconnected.
- Factories would keep producing “out-of-date” equipment because they were told to do so from central committee and because they kept getting paid to do so (in *beznal*) even though devices weren’t getting used.
- In addition to consumer uses, the Soviet Union had a habit of stockpiling huge amounts of equipment in expectation of war/conflict

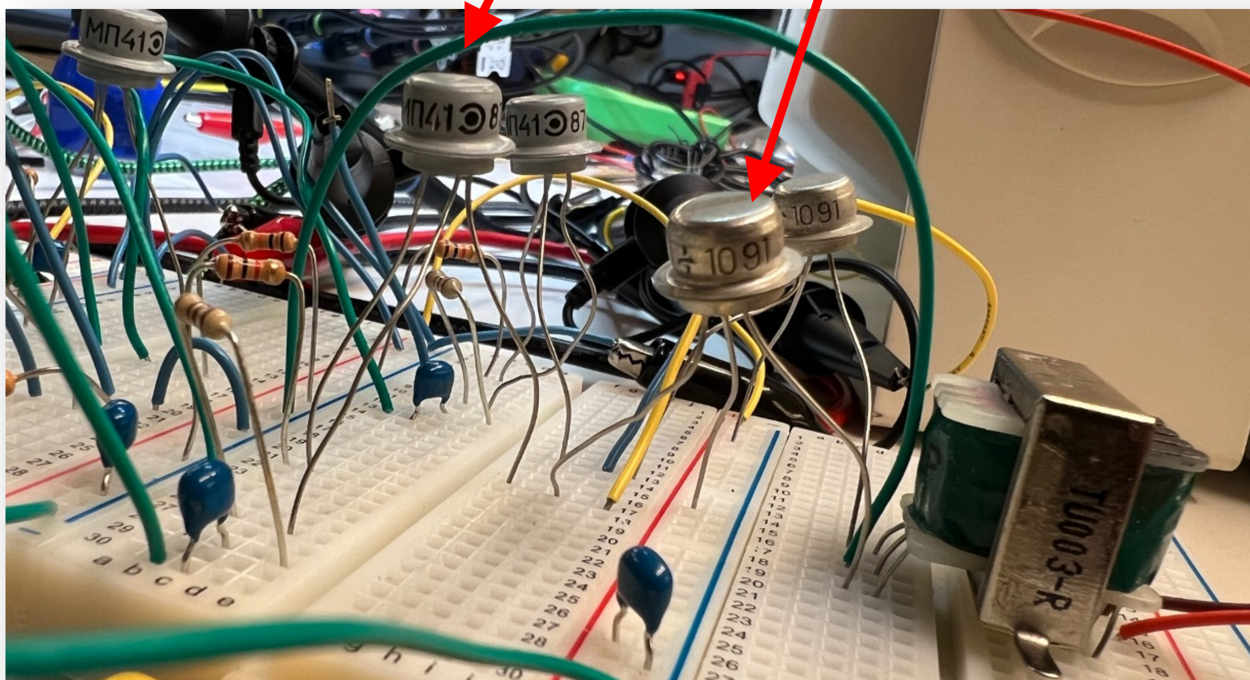
The Result

- Soviets were still making and stockpiling huge amounts of vacuum tubes and 1950s-style transistors up until the early 1990s
- When the USSR collapsed into its disparate republics, you had these huge stockpiles of vintage equipment exposed to west
- Sort of like a time-capsule
- Factories and warehouses that would have been torn down/burned in the West decades before were still there and people have been selling these things off ever since.

Right Up Until the End

МП41 МП20

(date code October 1991 😬)



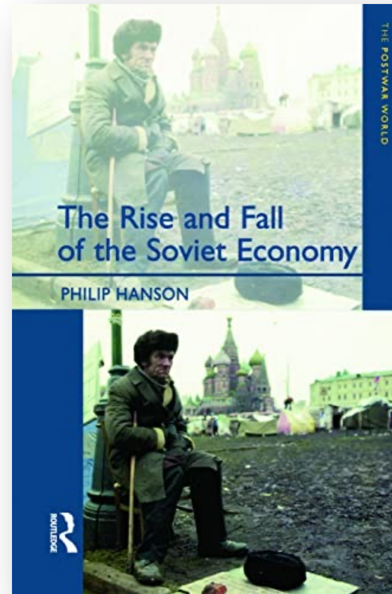
- Soviet Union dissolved in December 1991

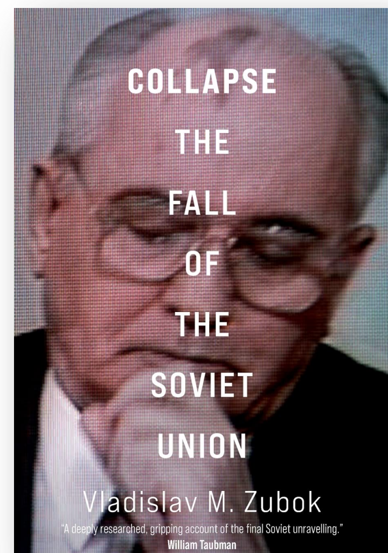
Example

- A used Raytheon CK721 costs about 60 USD on Ebay.
- I can get a 100 MP41 transistors (a somewhat similar set of specs) for about 10 USD from Ukraine over Ebay depending on model
- Same with lots of other equipment
- So yeah you have to read Cyrllic a bit, but the datasheets are out there if you need germanium transistors

Further Reading

- In case you're interested in this, these books don't cover much in the way of electronics, but do discuss the Soviet economic system a lot
- *The Rise and Fall of the The Soviet Economy: An Economic History of the USSR from 1945* by Philip Hanson
- *Collapse: The Fall of the Soviet Union* by Vladislav Zubok





So What About Tubes?

- Did they Just disappear?....no
- Vacuum tubes continued to be better at high frequencies for several decades
- Plus also just technical momentum
- A few tube variants tried to delay the inevitable, however

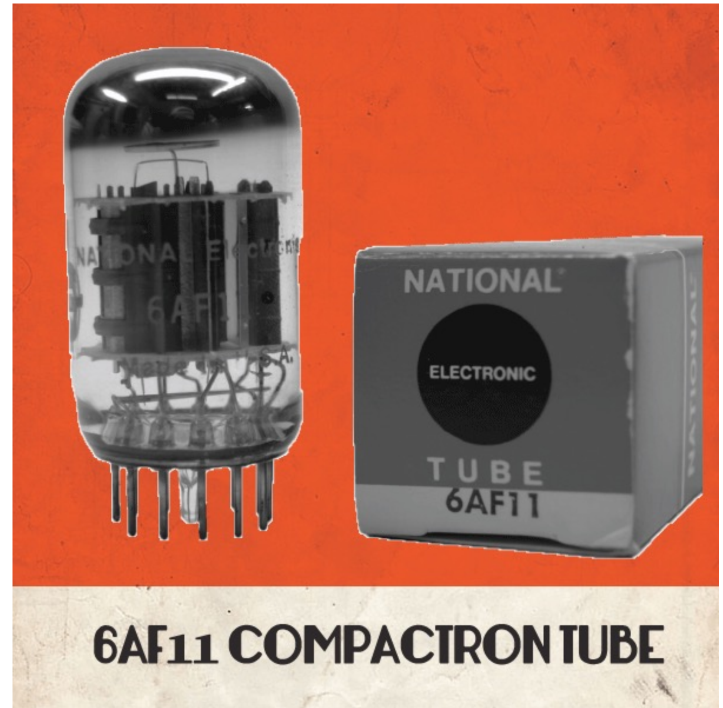
	Point Contact Type	Junction Type	Tubes
Gain	20 - 30 db	30 - 50 db	20 - 50 db
Efficiency (Class A) (Class C)	30% 90%	45 - 49 % 95%	1 to 25 % 70%
Life	70,000 hrs.	90,000 hrs.	5,000 hrs. ?
Vibration	100 g	100 g	
Shock	20,000 g	20,000 g	
Uniformity	±3 db	±2 db	±3 db
Minimum Powers	1 mw.	1 microwatt	1/10 watt
Temperature	70° C	70° C	500° C
Frequency	30 - 70 mc	3 - 5 mc	60,000 mc
Gain X Bandwidth	1000 mc	120 mc	1000 mc
Noise Figure	45 db	15 db	10 - 30 db
Maximum Power	100 mw	1 watt	1 megawatt

Summarizing - up to 30 mc, transistors can do a better job than tubes within the limits of power and temperature.

1952 analysis of pros/cons of tubes vs. transistors

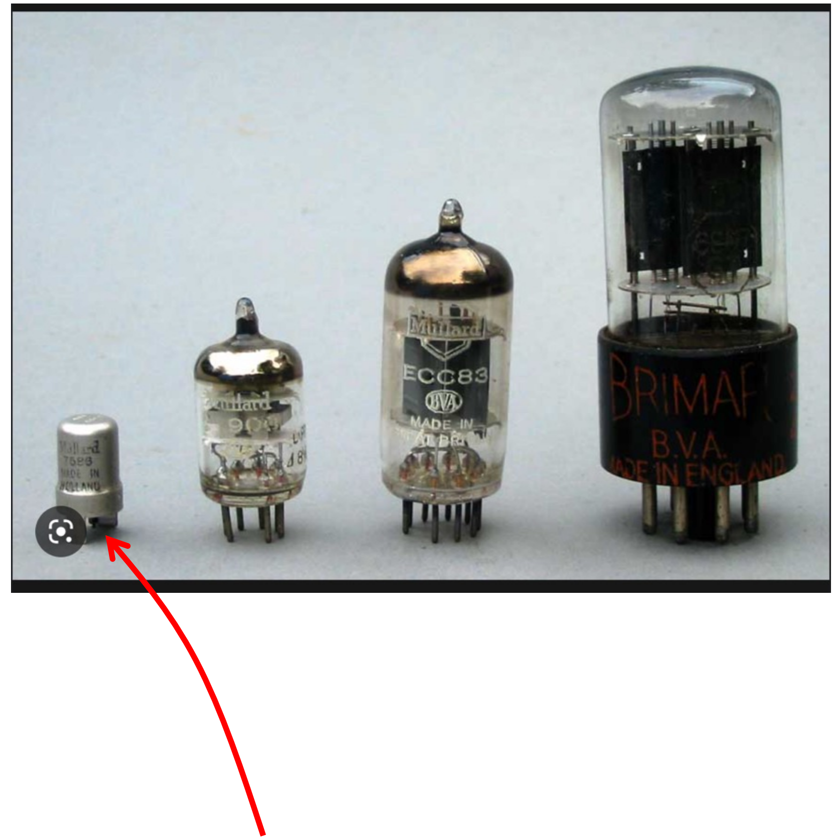
Compactrons

- 12-pin tubes that would often incorporate three or four triodes or pentodes into one internally-wired package.
- The idea was to provide better self-contained integration than transistors could for a little while.



Nuvistors

- Developed by RCA in 1959
- From outside they look like an early transistor
- On inside they were a tiny vacuum tube.
- Good for high frequency stuff and stayed competitive with tubes up through early 1970s



1975 Ad:

- But even by the 1970s, TVs, which were one of the last holdouts* had started to fully transition

"100% solid state" is a selling point!

*because TV signals were at very high frequencies

Vacuum Tubes Sort of Disappeared

- That was the end
- It took until the mid-seventies for transistors to be cheap enough and work at higher frequencies, so vacuum tubes tuck around in TVs for a while
- By the mid-seventies, you just didn't see them anymore
- Almost Everything was solid state by the eighties.
- Few exceptions:
  - Microwave Ovens (Cavity Magnetron is technically a vacuum tube)
  - Some high-frequency/power transmitting systems still use very special flavors of vacuum tube, but every year that goes by, more and more of these are getting replaced by solid state designs as that tech continues to advance

Transistors Replaced Everything

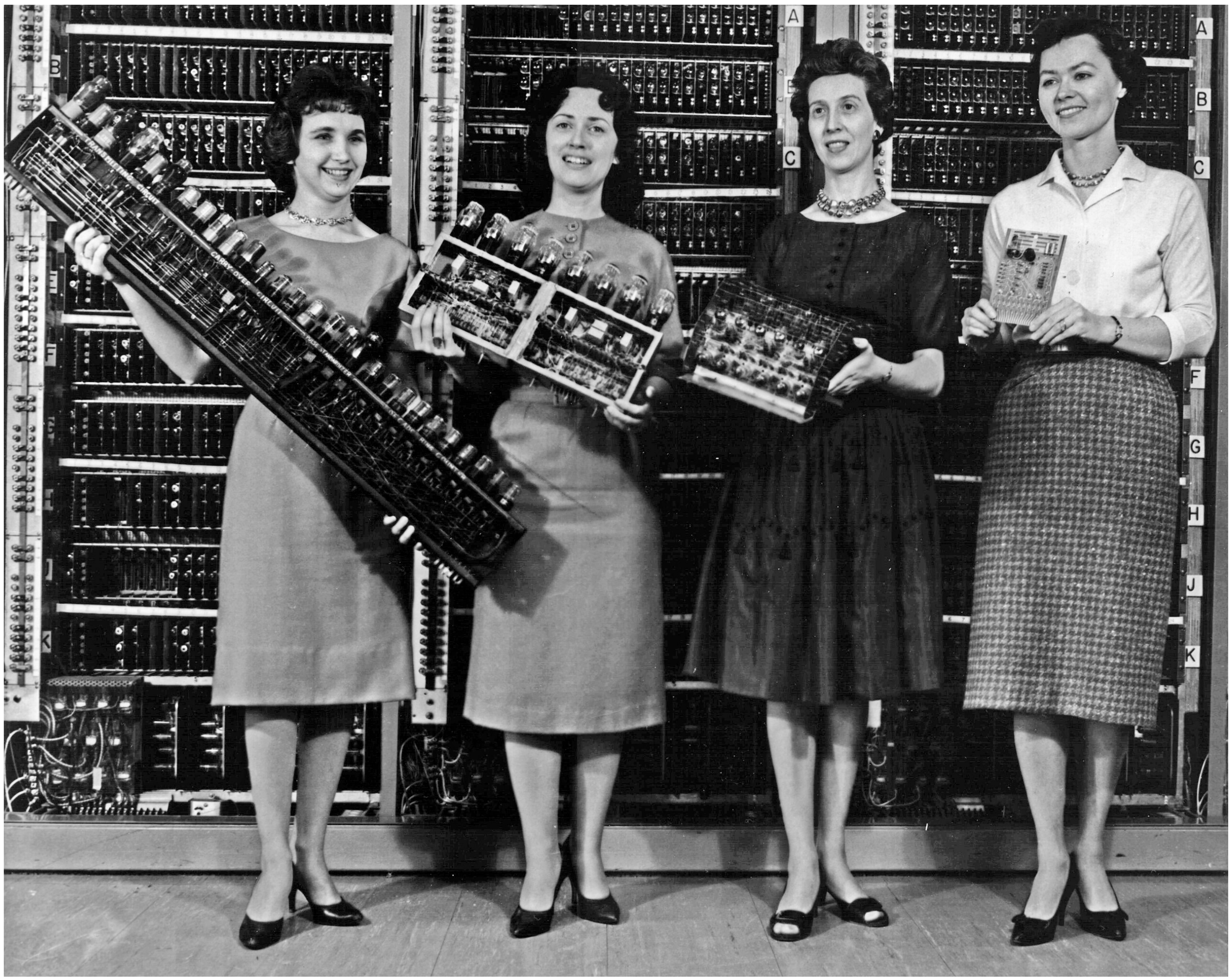
- Anywhere you'd have used tubes transistors came in and replaced.
- Transistors also allowed high-density assembly which necessitated the development of printed circuit boards
- They were also a technology that could shrunken and assembled together into pre-made packages (integrated circuits)
- The real "scaling" of electronics began with transistors right around 1960

Early Computers

- Many systems that needed lots of active elements (computers) kept using tubes into the early 1960s.
- Transistors were expensive so unless you were the government which basically didn't care about cost, or you were making high-end consumer electronics, you still saw tubes.
- But even by early 1960s transistors got robust enough and cheap enough that computers started to transition as well

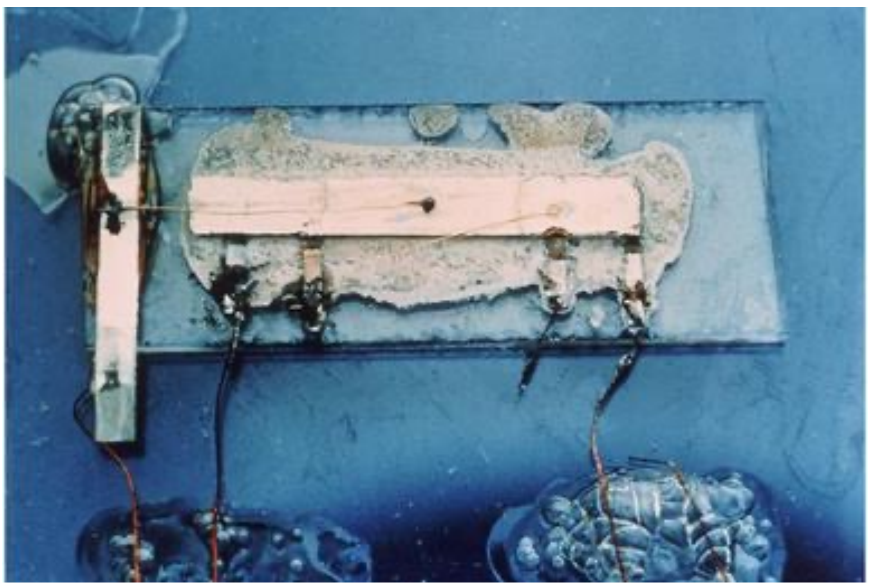
Transistors Replaced Everything

- 1961 photo showing off the “massive” scaling of equivalent circuit boards from ENIAC (1945, left) to BRLESC (1962, right)



Integrated Circuits

- Jack Kilby (@ TI) and Bob Noyce (@ Fairchild) both kinda developed the integrated circuit right around 1958/59



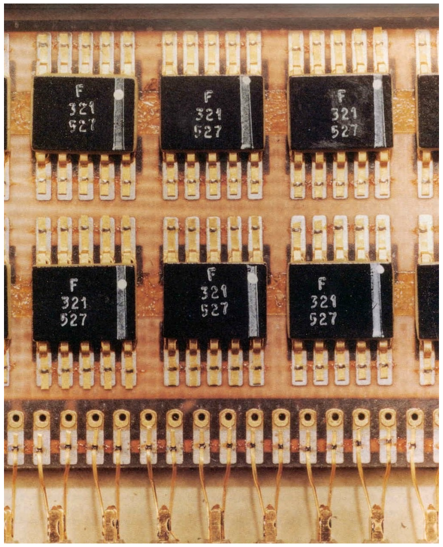
First Integrated Circuit by Jack Kilby

Kilby

Noyce

Early Integrated Circuits

- Early Integrated Circuits would be in "flatpacks" which were replaced by "Dual Inline Packages (DIPs)" by the late 1960s

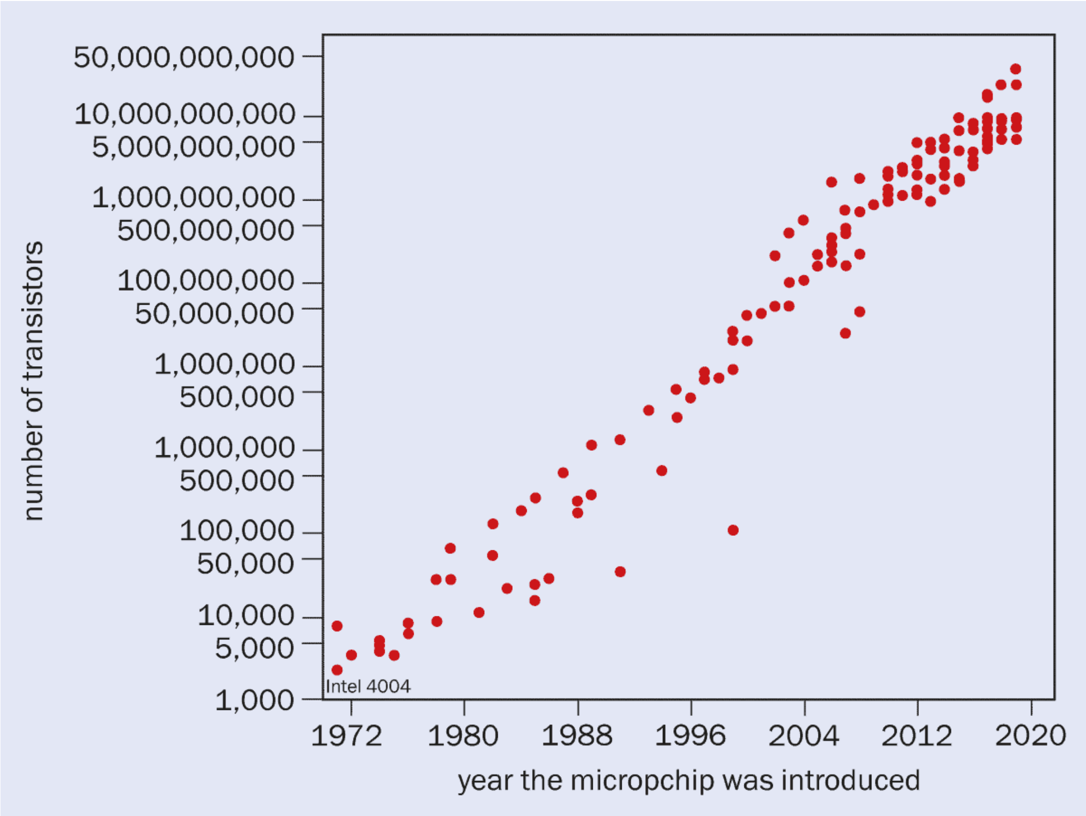


Apollo Guidance Computer built completely from 3-input NOR gates in flatpacks

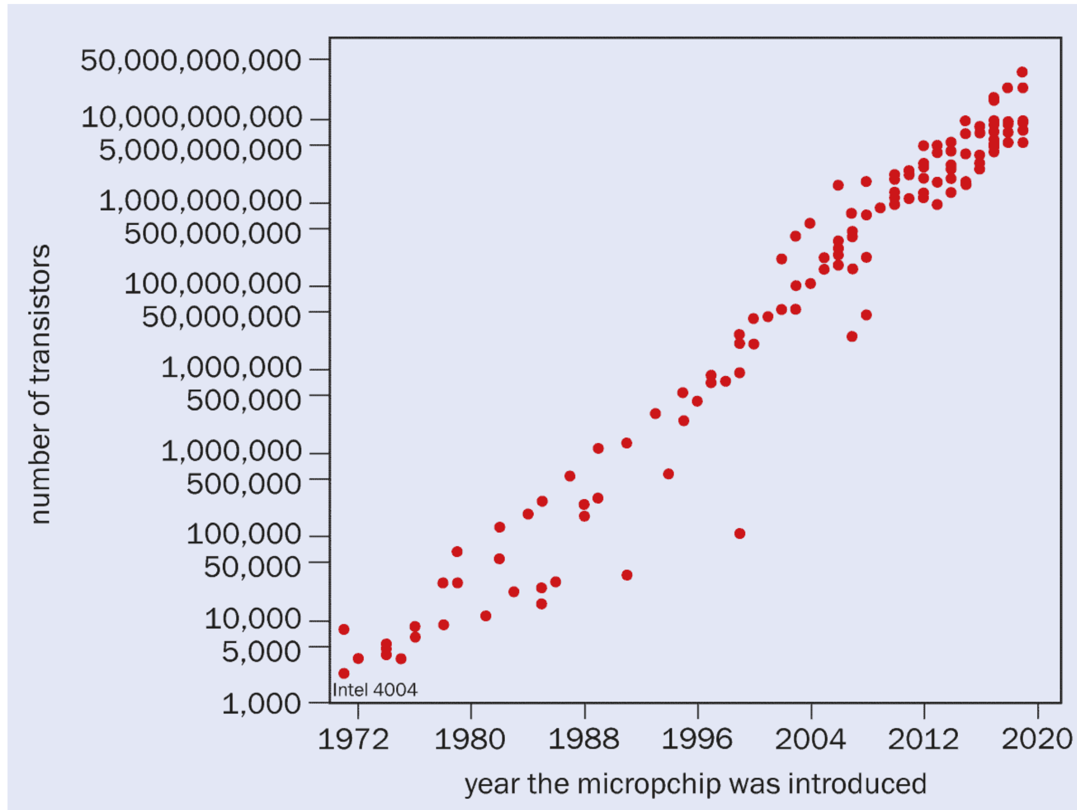
https://en.wikipedia.org/wiki/Flatpack_(electronics)

And things just kept going…

- 1971: Intel (spinout of Fairchild, which was spinout of Shockley) releases 4004, first commercially available single-chip computer (4 bit lol)
- Gordon Moore made his prediction-kinda thing



And things just kinda kept going and going…

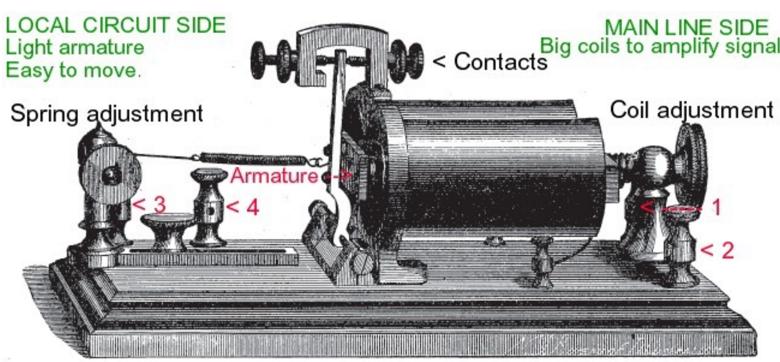


- 2022 Apple M2 processor has 20 billion transistors on it

And things just kinda kept going and going…

- The only real constant in all of this is change (and your basic circuit laws)

Aldini Reanimating an Ox Head



1840

2023

Where to Go From Here

- Anyways…we'll end it here.
- Lots of tubes out there.
- Lots of transistors
- Lots of stuff…every year stuff goes obsolete.
- Build stuff with them
- Appreciate them…you'll appreciate modern stuff all the more.